SYSTEM ANALYSIS FOR BIOGAS PRODUCTION FROM PALM OIL MILL EFFLUENT AT MESOPHILIC AND THERMOPHILIC CONDITIONS

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A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING
IN ENERGY TECHNOLOGY AND MANAGEMENT

THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT
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ABSTRACT

An anaerobic hybrid reactor (AHR) was applied to treat and produce methane from raw palm oil mill effluent (POME) containing high concentrations of chemical oxygen demand (COD), oil and grease (O & G), and suspended solids (SS). AHR, the combination of anaerobic sludge bed and fixed film reactor, contains packed zone and sludge zone in the upper and lower parts of the reactor, respectively. Several influencing factors for the AHR process performance and stability, temperature is one of the major factors to study their effect. Therefore, this research was studied the effects of mesophilic (35°C) and thermophilic (55°C) temperatures on reactor performance, stability and microbial activities. The system analysis was applied in this study for decision making.

Two 6 L of cylindrical AHRs were operated at mesophilic (35 ºC) and thermophilic (55 ºC) temperature. The AHRs' performance and stability as well as microbial activity through optimization of maximize organic loading rate (OLR) and shortest hydraulic retention time (HRT) were carried out. The initial seed was collected from mesophilic anaerobic treatment system, and acclimatized to 55 ºC for thermophilic AHR. Specific glucose utilization (SGU), representing acidogenic activity, was 0.77 and 0.72 $gCOD_{glucose}/gVSS.d$ for mesophilic and thermophilic reactors, respectively. Specific methanogenic activity (SMA), representing methanogenic activity, was 0.27 and 0.17 $gCOD_{methane}/gVSS.d$ for mesophilic and thermophilic reactors, respectively. In addition, system analysis was used to determine in 3 aspects for financial, environment, and energy.

The AHRs successfully operated within 193 days. The operating condition was step increased from organic loading rate (OLR) 1.2 to 11.5 gCOD/l.d and hydraulic retention time (HRT) was reduced from 20 to 5.3 days. According to the results, it was found that the increasing of OLR and reducing of HRT were affected to the AHRs performance and stability as well as microbial activity, while the operating temperature did not significant affect to the process performance, process stability and microbial activity. The operating condition at OLR 7.5 gCOD/l.d and HRT 10 days showed the significant reactor performance and stability for the both AHRs. At mesophilic reactor (MR), the reactor performance can achieve at 80% of COD removal, 11 l/d of methane production and 0.30 $lCH_4/gCOD_{removed}$ of methane yield. pH was in the range of 7 – 8 and the ratio of TVA/Alk was lower than 0.5. Acidogenic activity in sludge and packed zones was 2.59 and 2.52 $gCOD_{glucose}/gVSS.d$, respectively. Methanogenic activity in sludge and packed zones was 0.20 and 0.24 $gCOD_{methane}/gVSS.d$, respectively. While at thermophilic reactor (TR), it can reach at 80% of COD removal, 13 l/d of methane production, and 0.34 $lCH_4/gCOD_{removed}$ of methane yield. pH and the ratio of TVA/Alk were in the same values of MR. Microbial activity of acidogens and methanogens in sludge zone was 2.78 $gCOD_{glucose}/gVSS.d$ and 0.21 $gCOD_{methane}/gVSS.d$, respectively. Whereas, acidogenic and methanogenic activities in packed zone were 2.01 $gCOD_{glucose}/gVSS.d$ and 0.21 $gCOD_{methane}/gVSS.d$, respectively.

The high AHR’s performance and stability were obtained at the condition of OLR 7.5 kgCOD/ m^3.d and HRT 10 days. The system analysis was applied in this operating condition by the assumption for 600 m^3/d POME generation with COD concentration 75 kgCOD/ m^3. Installation cost, operating and maintenance cost of mesophilic was lower than thermophilic plants. Profit of thermophilic was higher than mesophilic plants. There are payback periods (PP) was 2 years for both plants, internal rate of return (IRR) were 42% and 45% for mesophilic and thermophilic treatment plants, respectively. Net present value (NPV) was 189 and 208 million baht for mesophilic and thermophilic plants, respectively. The thermophilic treatment plant was recommended to investment, with higher than 10.28% of NPV, 7.4% of energy production and 6.5% of electricity production, than mesophilic treatment plant. The environmental analysis of GHG reduction found that the thermophilic treatment plant was slightly more than mesophilic treatment plant 7.38% of CO_2e.

Keyword: anaerobic hybrid reactor, mesophilic, operating condition, palm oil mill effluent, thermophilic, system analysis

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CHAPTER 1
INTRODUCTION

1.1. Rationale

The world's demand for energy is growing continuously, resulting in interest in alternative sources of energy. One of the interesting of renewable energy is the energy from bio-waste and palm oil waste is one of them for the energy production. Palm oil is an importance source for food production. In addition, it can use for biodiesel production which is a renewable energy and substitute the conventional diesel fuel. Palm oil is providing 43.1 million tones or 27% of the world's total edible oil and fat production, followed by soybean oil [1]. Oil palm plantations in Thailand are expanding year by year. There are large amount of waste that generated from a process of palm oil production. Palm oil mill effluent (POME), which is polluting wastewater and could not discharged directly to the environment [2], is generated from the palm oil production process. Typically, 1 ton of crude palm oil production generated POME approximately 5.0-7.5 m^3 [3]. POME is a viscous brown liquid consisting of suspended solid at pH ranges between 4 and 5 [4]. A characteristic of POME has high COD and BOD by approximately 90,000 mg/l and 30,000 mg/l, respectively [5]. POME was discharged at the temperature about 80-90 °C [6]. POME was shared the potential of biogas production with the total potential of the biogas production from agro-industrial waste in Thailand by 8.82% or 88.6 million m^3/year. With this potential was higher than the other source that had higher of feed stock than POME feed stock, except for cassava starch wastewater [7].

The a treatment of POME is also important to palm oil production, as POMEs contain large quantities of high organic pollutants and are classified as high strength wastewater. Biological treatment of POME is the most frequently used treatment method. There are many POME treatment methods, which are aerobic treatment, membrane treatment system, evaporator method, and anaerobic digestion method. Since POME was contained high concentrations of organic matter, adoption of anaerobic digestion in the first stage of the process is needed to convert the bulk of the POME to biomethane as renewable energy as well as treatment of POME in the same time. In term of energy for POME treatment operation, anaerobic digestion has more advantage than the other methods because less energy requirement and produce methane gas which is a value-added product [8], [9]. An anaerobic reactor have been studied in laboratory scaled for POME treatment such as upflow anaerobic sludge blanket (UASB) reactor, up-flow anaerobic filtration, fluidized bed reactor, and up-flow anaerobic sludge-fixed film (UASFF). The performances of these reactors were reported as a difference of advantage and disadvantage for each reactor [8]. Anaerobic hybrid reactor (AHR), which content sludge zone and packed zone, is a high rate anaerobic bioreactor with high performing in COD removal efficiency and methane production [8], [9]. Upflow AHR can work well for the high-suspended solid pollutants like cassava starch wastewater, slaughterhouse waste, and POME [4], [9].

Anaerobic digestion (AD) is a bioprocess that degrades complex organic matter by using a microbial consortium without oxygen. Four steps of AD to produce methane. There are hydrolysis, acidogenesis, acetogenesis, and methanogenesis [8]. The major components in biological anaerobic digestion, not only microorganisms play an important role as the main function in controlling reactor performance and stability but the operational and environmental parameters, which are pH, operating temperature, C/N Ratio, total solid content, alkalinity, nutrient, inhibiting and toxic materials, and also concern about loading and retention time, of the processes also obviously affect the microbial behavior resulting in wastewater treatment and biogas production performance. A one of importance factor that influence to the digester performance and microbial behavior is the operating temperature. The temperature ranges that suitable for anaerobic operation have been classified into mesophilic temperature range (30-35 ºC), and thermophilic temperature range (50-60 ºC). Normally, the mesophilic condition (below 45 ºC) has been widely used for wastewater treatment. Many previous studies have been known the thermophilic condition, which operated at the temperature of 49-57 ºC, gives more anaerobic digestion performance than the mesophilic condition [10], [11], and [12] with the POME temperature in sump pond varying between 45 and 70 ºC. It is generally recognized that thermophilic operation has the potential for a faster bacterial growth and consequently higher treatment rate [13]. Although, many studies found that the thermophilic digester has the performance more than the mesophilic digester. However, in term of energy requirement which use for control the temperature of digester, never investigated and compared with the energy production in form of biogas production was studied.

In this study, two anaerobic digesters, which are mesophilic (35 ºC), and thermophilic (55 ºC) anaerobic reactors, were compared for POME treatment by using an anaerobic hybrid reactor (AHR) with a content sludge zone and a packed zone. The performance and stability of the AHR at various organic loading rate (OLR) and hydraulic retention time (HRT) were measured in term of pH, total volatile acid (TVA), alkalinity (Alk), COD removal efficiency, biogas and methane production, and their yield. Microbial activity of the reactors will be investigated for understanding the effects of reactor temperature on reactor performance, stability and microbial activity. Morover, a system analysis was applied to study for determination the challenging of mesophilic and thermophilic POME treatment system, in term of finance, environment, and energy, to help investor for making the decision in biogas production and treatment system.

1.2 Research objectives

1.2.1 To study the effect of mesophilic and thermophilic temperatures on reactor performance and stability for POME treatment

1.2.2 To conduct a system analysis of POME treatment and biogas production at mesophilic and thermophilic temperatures in three aspects, which are finance, environment, and energy production.

1.3 Scope of research work

1.3.1 The source of seed sludge was obtained from the mesophilic anaerobic cover lagoon for POME treatment.

1.3.2 The laboratory reactor was an anaerobic hybrid reactor (AHR) for mesophilic (35 ºC) and, thermophilic (55 ºC) conditions.

1.3.3 The reactors performance and stability were studied on COD removal, biogas and methane production, pH, TVA, and Alk. The reactors were operated at maximum OLR and shortest HRT.

1.3.4 System analysis was conducted on the effect of operating temperature conditions in terms of finance, which consisted of cost and profit, environment, which consisted of organic waste degradable performance, and CO_2 and CH_4 emission reduction, and energy production, which were biogas and electricity production.

1.4 Expected results

This research was expected to analyze the system of POME treatment with mesophilic and thermophilic digesters. The results expected included:

1.4.1 The stability, performance parameter, and microbial activity of mesophilic and thermophilic digesters were used for the selection of POME anaerobic treatment systems.

1.4.2 The biogas production of mesophilic and thermophilic digesters used in system analysis and helped to the select the POME anaerobic treatment system.

1.4.3 The system that produces renewable energy at the maximum benefit was suggested for alternative POME anaerobic treatment systems at different operating temperatures.

CHAPTER 2
THEORIES

2.1 Palm oil production

2.1.1 Oil palm plantations in Thailand

The oil palm plantation and the palm oil industry in Thailand are comparatively young. In 2005, the oil palm plantation area was 2.75 million rai (2.5 rai = 1 acre) and increased to 4.49 million rai in 2012 with production yields of 2,469 and 2,743 kgFFB/rai, respectively. The oil palm plantation was expanded year by year as shown in Table 2.1. The palm oil industry has developed very fast in recent years. In 2012 there were 80 palm oil mills in operation with an overall production capacity of 10-12 million ton FFB/year. Fifteen mills share about 70 % of the total palm oil production capacity, equal to about 2.5 million ton crude oil per year [5]. Both, the plantations and the mills have a high potential for further optimization in terms of agricultural and production technology. Because of the concentration of palm oil plantation and mills in Southern Thailand, this industry is of dominant importance in terms of work provision and generation of income to local people.

Table 2.1 Oil palm plantation in Thailand [5]

Year	Oil palm plantation area (million rai)	Products (million ton)	Yield (kgFFB/rai)
2005	2.75	5.00	2,469
2006	2.95	6.72	2,828
2007	3.20	6.39	2,399
2008	3.68	9.27	3,214
2009	3.89	8.67	2,561
2010	4.08	8.22	2,315
2011	4.28	9.88	2,631
2012	4.49	10.94	2,743

2.1.2 Palm oil

The world’s demand for energy grows rapidly. An alternative source of energy, such as renewable energy, is be coming of much interest. One of interesting renewable energy, there are the energy from biomass. A growing of world population has effect to rising of energy demand and also food demand. Oil and fat are an importance food in the world, one of them is oil palm. Oil palm is the world’s largest source of edible oil with 25% of the world total edible oil. About 90% of palm oil is used as food, and 10% is used as raw material of soap production. Many developing countries are increasing the palm oil production, for example, Malaysia, Indonesia, and Thailand. 44% of total world’s palm oil production is Indonesia, 43% and 2% are Malaysia and Thailand, respectively [14], as shown in Figure 2.1.

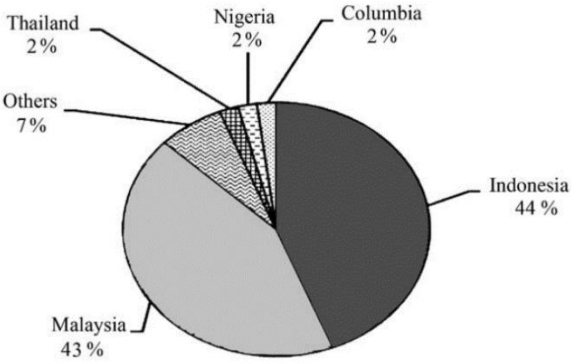

Figure 2.1 World producers of palm oil in 2006 [14]

The two main products, produced from palm oil production processes are crude palm oil (CPO) and crude palm kernel oil (CPKO). The main by-products and wastes that produced from palm oil mill are empty fruit bunches (EFB), palm oil mill effluent (POME), fiber and shell, which the biomass wastes are EFB, fiber and shell. Palm oil mill process starts from feeding of fresh fruit brunch (FFB). The composition of FFB was show in Figure 2.2. The average percentage of the FFB composition found from survey. There are 28% EFB, 12% palm press fiber (PPF) or fiber, and 8% palm kernel shell (PKS) or shell [2].

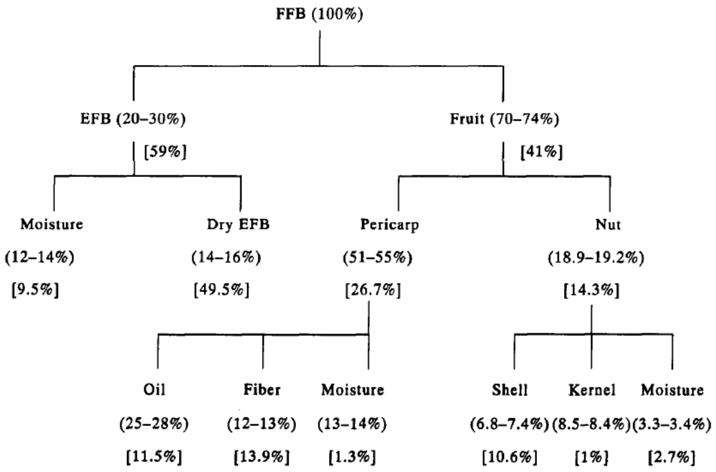

Figure 2.2 Composition of FFB [2]

Symbol remark: ( ) refers to high-quality FFB and [ ] refers to low-quality FFB

2.1.3 Palm oil milling processes

The schematic flow diagram of a palm oil mill process is shown in Figure 2.3. The processes start from feed FFB into the processes. The processes included by sterilization, stripping, digestion and oil extraction [5].

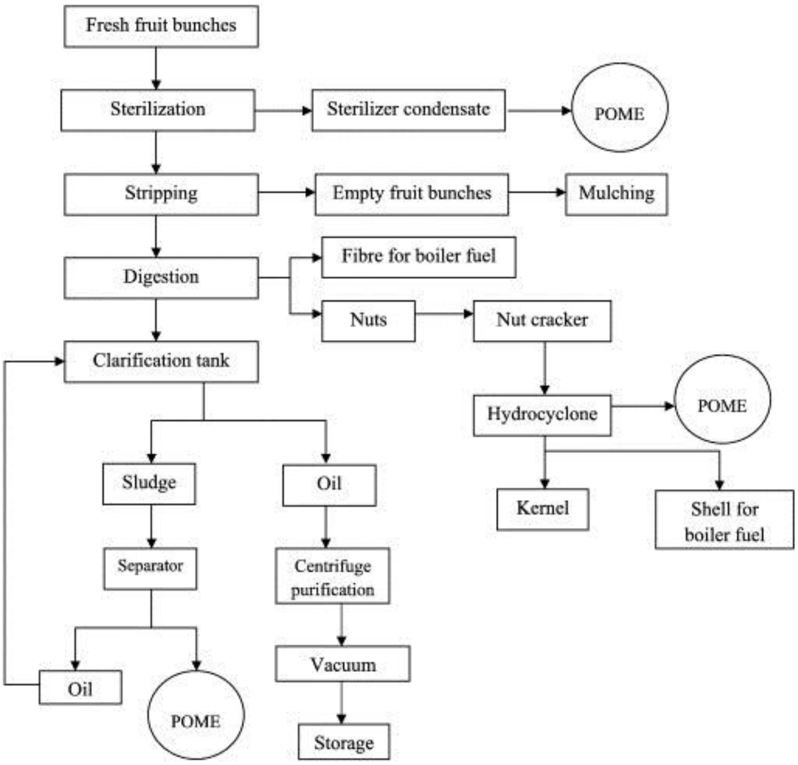

Figure 2.3 Flow diagram of palm oil milling process [5]

Sterilization of the FFB is done batch wise in autoclaves of 20 to 30 ton FFB capacity. Depending on that capacity 7 to 9 containers of FFB can be put into the “sterilizer”. Sterilization of FFB is done with the application of “live steam”.

The FFB is sterilized in order to inactivate the natural enzymes that stop the splitting of fat into free fatty acids (FFA) with the subsequent loss of oil. In addition, the sterilizing process loosens the fruit of the FFB, and softens the mesocarp, resulting in easier extraction of oil.

Stripping operated with the containers with the sterilized bunches are emptied into rotary drum threshers where the fruits are separated from the bunch stalks. The empty fruit bunches (EFB) are at present often separately stored for incineration to reduce the mass of residues and for simultaneous production of ash which has plant fertilizing value.

Table 2.2 shows output data of the different production processes applied in the “oil room”. Since steam consumption has been considered only in respect to the generations of polluted effluent, the total mass balance for steam in the production and utilization areas (production of electricity, etc.) is not included in Table 2.2.

Table 2.2 Output-balance of “standard wet process” [5]

Medium	Type of material	Individual mass (kg/t FFB)	Individual oil content (kg/t FFB)	Oil loss rel. to total loss (%)
Liquids	raw oil PO	163	0	0
	Washing/cooling water (except indirect cooling water)	depending on local conditions	0.5	3
	Steriliser effluent	150		
	Underflow of settling tank after centrifugation (separator) with a suspended solid load of > 30 kg/t FFB	742	7	41
Total		1055	7.5	44
gas/vapor	water vapors	250	0	0
Total		250	0	0
Summary total		1800		
Oil loss			17	

2.2 Palm oil mill effluent (POME)

The wastes generated from palm oil milling processes are EFB, POME, fibers and shells (Sumathi et al., 2008), POME was generated from the section of separator sludge (75%), which there are sterilizer condensate (17%) and hydrocyclone waste (8%). POME was discharged at the temperature of 80-90 °C. POME characteristics are shown in Tables 2.3 and 2.4.

Table 2.3 Characteristics of POME in Thailand

Parameter[a]	O-Thong et al., 2008 [16]	Nuntakumjorn et al., 2010 [17]	Meesap et al., 2010 [18]
BOD	22,000-54,300	n/a	n/a
COD	75,200-96,300	80,000-95,000	24,000
TS	35,000-42,000	58,000-62,000	n/a
SS	8,500-12,000	5,300	11,000
Oil & Grease	8,300-10,600	4,600-5,100	2,300
TKN	830-920	n/a	n/a
pH	4.2-4.5	4.4-4.6	4.6
Temperature	70-80	n/a	65

Note: [a] All parameters are in mg/L except pH (no unit) and temperature (°C)

[b] n/a refers to data unavailable

Table 2.4 Characteristics of POME in other countries

Parameter[a]	Najafpour et al., 2006 [4]	Fang et al., 2011 [20]
BOD	23,000-26,000	n/a
COD	42,500-55,700	97,000
TS	n/a	67,300
SS	16,500-19,500	40,600
Oil & Grease	4,900-5,700	n/a
TKN	500-700	3,200
pH	3.8-4.4	4.3
Temperature	n/a	80-90

Note: [a] All parameters are in mg/L except pH and temperature

[b] n/a refers to data unavailable

Table 2.5 shows the potential of palm oil wastewater for convertsion to energy, and was compared with other industry wastewater. The table showed that the energy potential from the wastewater of palm oil production can be generated the energy about 2,690 kt/y by 1 m^3/t of wastewater and produce methane 27.16 $ktCH_4$/y.

Table 2.5 Energy potential of industrial wastewater in Thailand [21]

Industries	Output (kt/y)	Wastewater (m^3/t)	COD (kg/m^3)	COD loading (kt/y)	CH_4 generation ($ktCH_4/y$)
Slaughterhouse	276.57	74.54	2.28	47.09	9.14
Sugar	6,188.00	11.82	2.93	214.45	41.60
Distillery	916.26	3.40	25.30	78.82	15.29
Brewery	756.81	4.12	2.73	7.38	1.43
Milk	1,012.06	4.05	1.28	5.23	1.01
Monosodium glutamate	102.93	39.20	16.49	66.16	12.90
Coffee	12.28	21.77	2.60	0.70	0.14
Instant noodle	136.41	76.97	2.38	25.03	4.86
Starch	1,906.29	24.72	7.65	356.11	69.09
Palm oil	2,690.00	1.00	52	140.00	27.16

Table 2.6 shows the status of biogas feed stock and the potential of biogas production from agro-industrial waste. The agro-industrial waste was shared with the animal farm waste and municipal solid waste by 34%. There are the wastes from cassava starch, cassava pulp, crude palm oil, ethanol, canned tuna, canned pineapple, sugar, and slaughterhouse production. The waste from palm oil production was shared the potential of biogas production with the total potential of the biogas production from agro-industrial waste by 8.82% or 88.6 million m^3/year. POME has feed stock lower than other sources but higher the potential ratio of biogas production because POME has higher COD than the other sources.

Table 2.6 The status of biogas feed stock and potential of biogas production from agro-industrial waste [22]

Sources	Feed stock (million m^3/year)	Biogas production (million m^3/year)	Potential ratio (%)
Cassava starch wastewater	34.4	354.71	35.29
Cassava pulp wastewater	3.9	384.62	38.24
POME	2.5	88.6	8.82
Ethanol wastewater	5.9	29.56	2.94
Canned tuna wastewater	18.8		
Canned pineapple wastewater	4.8		
Sugar wastewater	7.9		
Slaughterhouse wastewater	2.1		

The processes of palm oil production generate liquid wastes, that called palm oil mill effluents (POME). Raw POME is included by colloidal suspended containing 95-96% water, oil 0.6-0.7%, and total solid 4-5%. POME con not discharge directly to environmental, because there are very high COD about 78,000 mg/l, oil and greases about 8,370 mg/l, total solid about 43,635 mg/l and suspended solid about 19,020 mg/l [23]. If the untreated POME will be discharged to water sources, that is an environmental problem cause. A treatment of POME technology is required. There are many technologies for POME treatment, which are anaerobic, aerobic, membrane, and evaporation. The anaerobic digestion method is the best technology of POME treatment in term of energy requirement and has stronger advantage than other technologies as show in Table 2.7.

Table 2.7 Advantages and disadvantages of anaerobic treatment [8]

Treatment type	Advantage	Disadvantage
Anaerobic	- Low energy requirement - No aeration - Produce methane gas as a valuable product - Generated sludge from process could be used for land application	- Long retention time - Slow start-up (granulating reactors) - Large area required for conventional digesters

2.3 Principle of anaerobic digestion

Anaerobic digestion is the biochemical processes, which includes four steps to produce methane (CH_4) from complex organic matters in the absence of oxygen condition. There are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. By bacteria consume the organic matters for their growing. The mainly products from anaerobic digestion are CH_4 and CO_2 and also produce other gases which are NH_3 and H_2S as follow below reaction. Figure 2.4 shows the steps of anaerobic digestion to produce methane.

$$\text{Organic matter} \rightarrow CH_4+CO_2+H_2+NH_3+H_2S$$

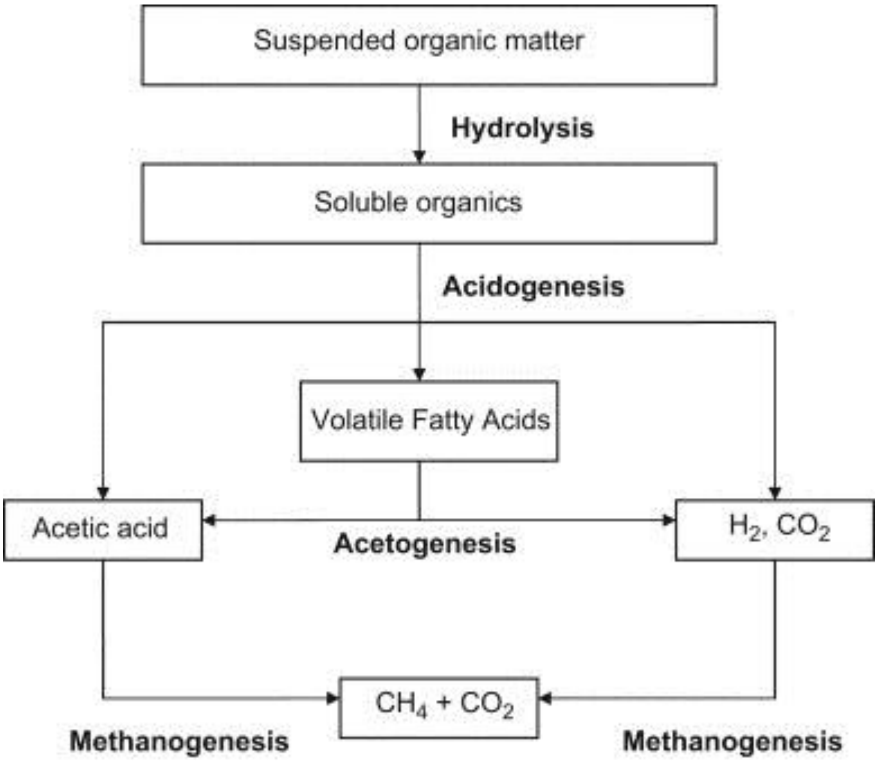

Figure 2.4 Subsequent steps in the anaerobic digestion process [24]

2.3.1 Hydrolysis

Complex organic matter, such as proteins, carbohydrates, and lipids, will break down into soluble monomer molecules by hydrolyzing bacteria. Monomer molecules are amino acids, glucose, fatty acid, and glycerol [25].

2.3.2 Acidogenesis

Acidogenesis is the use of Acidogenic (acid-forming) bacteria to convert the products, which are amino acids, glucose, and fatty acids, from the hydrolysis stepto organic acid, alcohol, ketone, acetate, CO_2 and H_2. Organic acids include acetic, propionic, formic, lactic, butyric, and succinic acids. Alcohols and ketones are ethanol, methanol, glycerol and acetone. Acetate is the main product from carbohydrate fermentation [25].

2.3.3 Acetodenesis

Acetogenicbacterias is used in this step. These bacteria convert fatty acid and alcohols into acetate, CO_2 and H_2. Ethanol, propionic and butyric acid are converted to acetic acid by these bacteria as well, as shown in following reaction [25].

$$CH_3CH_2OH \text{ (ethanol) } + CO_2 \rightarrow CH_3COOH \text{ (acetic acid) } + 2H_2$$

$$CH_3CH_2COOH \text{ (propionic acid) } + 2H_2O \rightarrow CH_3COOH \text{ (acetic acid) } + CO_2 + 3H_2$$

$$CH_3CH_2CH_2COOH \text{ (butyric acid) } + 2H_2O \rightarrow 2CH_3COOH \text{ (acetic acid) } + 2H_2$$

2.3.4 Methanogenesis

This step uses Methanogenicarchaea to convert CO_2, H_2, and acetic acid into methane (CH_4). Methanogenicarchaea grow slowly in the wastewater. There are generation time ranges between 3 days at 35 °C and 50 days at 10 °C. Methanogen are divided into two categories. There are Hydrogenotrophic methanogens, which convert CO_2 and H_2 into CH_4, and Acetotrophic methanogens, which convert acetic acid into CH_4.

2.4 Factors influencing anaerobic digestion performance

There are important factors that affect anaerobic performance and anaerobic stability. The performance and stability of the digester depend on reactor configuration, hydraulic retention time (HRT), organic loading rate (OLR), pH, nutrients, operating temperature, inhibitor concentrations, concentration of total volatile failure and low process efficiency. These parameters required investigation of optimum conditions. One of major factor is the operating temperature, because anaerobic digestion is the biochemical process that utilizes organic matter for methane gas production. Most of methanogenicarchaea are active in two temperature ranges, there are mesophilic range between 30 and 35 °C and thermophilic range between 50 and 60 °C. At the temperature between 40 °C and 50 °C, all methanogenicarchaea are inhibited. The performance and stability of mesophilic and thermophilic digesters were review and reported in literature review. According to the discharge temperature of raw POME is about 80-90 °C that raw POME suitable for the both of mesophilic and thermophilic digesters.

2.4.1 pH

Anaerobic digestion is highly pH dependent. The optimal pH range for methanogen is 6.8-7.2, while for acid-forming bacteria, a more acid pH is desirable. The pH of the anaerobic system is typically maintained between methanogenic limits to prevent the predominance of the acid-forming bacteria, which may cause V&A accumulation. It is essential that the reactor content provide enough buffer capacity to neutralize any eventual V&A accumulation, and thus prevent build-up of localized acid zones in the digester. In general, sodium bicarbonate is used for supplementing the alkalinity since it is the only chemical, which gently shifts the equilibrium to the desired value without disturbing the physical and chemical balance of the fragile microbial population [26].

2.4.2 Nutrients

The bacteria in the anaerobic digestion process requires micronutrients and trace elements, such as nitrogen, phosphorous, sulphur, potassium, calcium, magnesium, iron, nickel, cobalt, zinc, manganese and copper for optimum growth. Although these elements are needed in extremely low concentrations, the lack of these nutrients has an adverse effect upon the microbial growth and performance. Methane forming bacteria have relatively high internal concentrations of iron, nickel and cobalt. These elements may not be present in sufficient concentrations in wastewater streams from the processing of one single agro industrial product like corn or potatoes or the wastewater derived from condensates. In such cases, the wastewater has to be supplemented with the trace elements prior to treatment. The required optimum C:N:P ratio for enhanced yield of methane has been reported to be 100:2.5:0.5 [25]. The minimum concentration of macro and micronutrients can be calculated based on the biodegradable COD concentration of the wastewater, cell yield and nutrient concentration in bacterial cells. In general, the nutrient concentration in the influent should be adjusted to a value equal to twice the minimal nutrient concentration required in order to ensure that there is a small excess in the nutrients needed.

2.4.3 Operating temperature

Anaerobic digestion can be operated at different temperature ranges, which are mesophilic temperature (30-35 ºC) and thermophilic temperature (50-65 ºC). Most of anaerobic digestion was operated at mesophilic temperature range. However, many studies found that the thermophilic temperature is an alternative operation system to produce more biogas and enables higher OLR, shorter HRT than mesophilic temperature [25]. The cause of temperature that effected to process performance and stability, there are the effect of temperature on the growth rate of microbial activity. Some of methanogens can be observed at individual temperature range, as shown in the Table 2.8.

Table 2.8 Optimum growth temperature of some methane-forming bacteria [27]

Genus	Temperature range (ºC)
Methanobacterium	37-35
Methanobrevibacter	37-40
Methanoaphaera	35-40
Methanothermus	83-88
Methanococcus	35-40
	65-91
Methanocorpusculum	30-40
Methanoculleus	35-40
Methanogenium	20-40
Methanoplanus	30-40
Methanospirillum	35-40
Methanococcides	30-35
Methanohalcbium	50-55
Methanohalephilus	35-45
Methanoluus	35-50
Methanogurcina	30-40
	50-55
Methanothix (Methanosaeta)	35-50

Khemkhao et al., [13] studied the effects of temperature and organic loading rate in UASB reactors that produce biogas from POME. Their results shown that the performance and stability of mesophilic and thermophilic reactors were not significant difference (lower than 4%). These effects were occurred on the cause of source of seed sludge. The initial seed was selected from mesophilic anaerobic digestion reactor and applied to the thermophilic reactor of this study. Some of acidogens and methanogens from mesophilic condition were observed in thermophilic condition. However, the results from this study were shown the mesophilic and thermophilic temperature conditions were suitable for POME anaerobic digestion treatment method.

Meesap et al., [9] was studied the performance of mesophilic anaerobic hybrid reactors for the treatment of POME. Their results were shown that the reactor can be operated for maximum condition at OLR 7.5 gCOD/l.d and HRT 5 days with the COD removal was 80 % and methane yield was 0.31 $l_{CH4}/gCOD_{removal}$ of the reactor performance. The most of methanogens species were the acetoclasitic *Methanosaeta*, the hydrogenotrophic *Methanobacterium* sp., and the hydrogenotropic *Methanomicrobiaceae*. These methanogens were supported the good environment condition and high performance inside the reactor.

Poh et al., [28] studied the thermophilic upflow anaerobic sludge blanket-hollow centered packed bed (UASB-HCPB) reactor for POME treatment. Their results were shown that the reactor can be operated normal and good environment condition at the temperature of 55 ºC with 88 % of COD removal and 90 % of BOD removal at an OLR 28.12 g/l.d, and produced biogas with 52 % of methane.

Ahn et al., [10] studied a comparison of two anaerobic filters, of which one was mesophilic (35 ºC) and the other of thermophilic (55 ºC). The anaerobic filters were operated by using a starch-based feed at variation of OLR. The digesters were operated by using the circulation of water to maintain a temperature at 55 ºC and 35 ºC. The working volume were 1.55 l and 1.52 l for thermophilic and mesophilic anaerobic filters respectively. The feed was pump to the reactors at HRT of 6.24 hr. and OLR up to 17 kgCOD/m^3d. The performance of the reactors were analyzed by the values of pH, alkalinity (mg/l), SCOD (mg/l), SS (mg/l), gas production (l/d), and methane yield (l CH_4/kg COD). The study was found that at the performance evaluation were no real difference between the two modes of operating, when OLR increased (OLR of 12.4 and 17 kgCOD/m^3.d), the performance of the reactors were more difference than lower OLR. For the performance at OLR 12.4 kgCOD/m^3.d, the SCOD removal of thermophilic filter (93 %) was higher than mesophilic filter (78 %), and the methane production of thermophilic filter was 4.98 l/d, which higher than mesophilic filter (3.19 l/d). At the OLR 17 kgCOD/m^3d, the SCOD removal was found

88 % and 55% for thermophilic filter and mesophilic filter respectively. The methane production was 6.18 l/d and 2.24 l/d for thermophilic filter and mesophilic filter respectively.

Yu et al., [11] studied the performance of mesophilic and thermophilic acidogenic upflow reactors. Each reactor was operated at 37 ºC and 55 ºC, and with a synthetic wastewater at a series of OLR. The reactors were water-jacketed, and one operated at mesophilic condition (37 ºC), and one operated at thermophilic condition (55 ºC). The reactors were operated with the OLR was increased from the initial 4 gCOD/l.d to 6, 8, 12, 16 and lastly 24 gCOD/l.d and each OLR was HRT 31-40 days. The characterization of wastewater was containing of carbohydrate 30.9 % of COD, protein 23.6 % of COD, and lipid 41.9 % of COD. That means the major components in the wastewater are carbohydrate, protein, and lipid, which equivalent to 94.6 % of COD. The performance of the reactor was analyzed in term of overall performance, COD reduction, and gaseous production, substrate degradation. The VFA/alcohol concentration of the two reactors had similar changing patterns. For the total biogas production at 8 gCOD/l.d was 0.98 l/l.d for the mesophilic reactor and 1.27 l/l.d for the thermophilic reactor. The COD removal was 16 % for the mesophilic reactor and was 15 % for the thermophilic reactor. The substrate degradation was found that, when OLR increased the degradation efficiency (%), which consisted of carbohydrate, protein, and lipid, was decreased, and the degradation rates of the three components in the thermophilic reactor were greater than the mesophilic reactor. The gaseous products were analyzed in component of acidogenic by-product, carbon dioxide, and hydrogen. At OLR 24 gCOD/l.d the methane no generated and the hydrogen partial pressure of mesophilic reactor was 33 kPa and 40 kPa for the thermophilic reactor. At OLR 4 gCOD/l.d the metane production of the mesophilic reactor was 31 kPa and 34 kPa for the thermophilic reactor. The result was showed 1.7-7.9 % of the COD in wastewater was converted to hydrogen or methane in the mesophilic reactor and 2.5-8.8 % of COD in the thermophilic reactor. The conclusion of this study was the wastewater discharged above ambient temperature could be operated by acidogenic reactor under either mesophilic or thermophilic condition.

Many studies have reported that thermophilic anaerobic digestion had slightly higher biogas production rate, COD and BOD removal, TSS removal, and higher OLR than the mesophilic digestion, which these are the values that used to evaluation the performance of anaerobic digestion. For the thermophilic digestion also had the pH, Alkalinity, and VFA concentration, which the values for demonstrate the process stability evaluation, greater than the mesophilic digestion. However, some of studies have shown that the difference between the mesophilic and thermophilic reactors performance was not significant. The thermophilic digestion had some disadvantage, for example the effect of temperature shift to operation temperature 55 ºC also sensitive than the temperature shift to 35 ºC. Finally, the POME could be treated by anaerobic digestion at mesophilic and thermophilic temperature ranges as well.

2.5 Anaerobic digestion for POME treatment methods

Poh et al., [8] which studied the development of anaerobic digestion methods for palm oil mill effluent treatment, and summarized all technologies that could be used in POME treatment and which anaerobic digestion technology was suitable in terms of energy requirements for POME treatment. The study also refer about the advantage and the disadvantage for each anaerobic treatment method. The results showed that the anaerobic digestion is an advantageous method for POME treatment that can generates the biogas, as a valuable product. The selection of anaerobic digester to appropriate with the characteristics of wastewater will be reducing the operation cost. The anaerobic digester can be able to treat POME wastewater into effluent, which satisfactory quality for wastewater discharge at lower cost, and the quality of the effluent is depended on anaerobic digestion method as well.

There are many alternative methods of anaerobic digestion suitable to POME treatment. The anaerobic digestion methods were divided into two sections; there are slow-rate anaerobic bioreactors and high-rate anaerobic bioreactors. Example for slow-rate anaerobic bioreactors is anaerobic pond method. Examples for high-rate anaerobic bioreactors are up-flow anaerobic sludge blanket (UASB) reactor, anaerobic filtration, fluidized bed reactor, and up-flow anaerobic sludge fixed-film (UASFF) reactor. At the moment, anaerobic contact digester and continuous stirred tank reactor (CSTR) were widely used for POME treatment. The summary about the advantage and disadvantage were show in Table 2.9. The organic loading rate, hydraulic retention time, methane production, and COD removal of each reactor were shown in Table 2.10.

2.5.1 Conventional treatment system

A Conventional system or ponding system is a common type of treatment system. Ponding system consisted of a deoiling tank, acidification ponds, anaerobic ponds and aerobic ponds. Size of pond depended on the capacity of POME and also an area available.

Ponding is the system that requires low cost and simple method. This system also requires long retention time and large area.

2.5.2 Anaerobic filtration

The digester was operated by the wastewater fed from the bottom of the reactor. Biomass attaches to the surface. The biogas that produced from anaerobic digester was leaved from the top of the reactor. This method requires a small reactor volume, operating on short retention time, but had high treatment efficiency. This method also requires a less cost of installation and operating. However, the digester has the problem of filter clogging for the continuous operation.

2.5.3 Fluidized bed reactor

The digester needed the biomass that attached and grows on the support material. This reactor requires very large surface areas. The digester is suitable to use for high-strength wastewater. However, many problems from the digester also occur. There are channeling, plugging, and gas hold-up. For treatment of POME, the digester has higher efficiency more than anaerobic filter.

2.5.4 Anaerobic contact digestion

The method is similar to common digesters, but the recycling of the sludge of the digester was used in this method. The problem of more O_2 in the digester causes this process to be less stable.

2.5.5 Continuous stirred tank reactor (CSTR)

CSTR is a closed tank digester with a mixer. The digester has improved the contact surface between wastewater and biomass. This system also produces more biogas production.

2.5.6 Up-flow anaerobic sludge blanket (UASB) reactor

This digester has a simple design where sludge from organic matter degradation and biomass settles in the reactor. The biomass granules will be digesting the organic matter when it has contact with sludge. UASB had widely used to POME treatment in many industrial. The digestion has high potential for biogas production, and appropriate to treat the wastewater that content high suspended solid. However, the problem of seed sludge also occur, if the seed sludge is not granulated, the start-up periods will be long.

Table 2.9 Advantages and disadvantages of various anaerobic treatment methods [8]

Methods	Advantage	Drawbacks
Conventional anaerobic digestion (pond and digester)	- Low capital cost - Low operating and maintenance cost - Able to tolerate big range of - OLR (pond) thus can easily - cope POME discharge during high crop season - Recovered sludge cake from pond can be sold as fertilizer	- Large volume for digestion - Long retention times - No facilities to capture biogas
Anaerobic filtration	- Small reactor volume - Producing high quality effluent - Short hydraulic retention times - Able to tolerate shock loadings - Retains high biomass concentration in the packing	- Lower methane emission - Clogging at high OLRs - High media and support cost - Unsuitable for high suspended solid wastewater
Fluidized bed	- Most compact of all high-rate processes - Very well mixed conditions in the reactor - Large surface area for biomass attachment - No channeling plugging or gas hold-up - Faster start-up	- High power requirements for bed fluidization - High cost of carrier media - Not suitable for high suspended solid wastewater - Normally does not capture generated biogas

Table 2.9 Advantages and disadvantages of various anaerobic treatment methods (cont')

Methods	Advantage	Drawbacks
UASFF	- Higher OLR achievable compared to operating UASB or anaerobic filtration alone - Problem of clogging eliminated - Higher biomass retention - More stable operation - Ability to tolerate shock loadings - Suitable for diluted wastewater	- Lower OLR when treating - Suspended solid wastewater
CSTR	- Provides more contact of wastewater with biogas through mixing - increased gas production compared to conventional method	- Less efficient gas production at high treatment volume - Less biomass retention
Anaerobic contact process	- Reaches steady state quickly - Short hydraulic retention time - Produces relatively high effluent quality	- Less stable due to oxygen transfer in digesting tank - Settle ability of biomass is critical to successful performance

Table 2.10 Performance of various anaerobic treatment methods in POME treatment [8]

Methods	OLR (kg COD/m^3day)	HRT (days)	Methane composition (%)	COD removal efficiency (%)
Anaerobic pond	1.4	40	54.4	97.8
Anaerobic filtration	4.5	15	63	94
Fluidized bed	40.0	0.25	N/A	78
UASB	10.63	4	54.2	98.4
UASFF	11.58	3	71.9	97
CSTR	3.33	18	62.5	80
Anaerobic contact	3.34	4.7	63	93.3

N/A; Data not available

Tables 2.9 and 2.10, suggest anaerobic treatment methods that show that a fluidized bed reactor has the highest OLR and shortest HRT. But fluidized bed reactor required very high energy requirement, so this methods may be not suitable for POME treatment for wastewater treatment and energy purpose. The second is UASFF that given higher OLR and shorter HRT than other methods, and given higher methane composition and also higher COD removal efficiency than other methods.

2.6 System analysis

Chiew et al., [1] studied the effective use of palm oil waste, especially on oil palm biomass, as energy resource in Malaysia. The study was analyzed the using of empty fruit bunches (EFB) to mulching and use to produce electricity as solid fuel for boiler. The study was estimated the scenarios, which concern about the distribution of the EFB source and optimal location for the installing of combined heat and power (CHP) plant for each scenario, scale of CHP plant, and transportation distance from palm oil mill to CHP plant. The systems were analyzed in term of profit and cost, avoided CO_2 emission, and energy saving. The results showed that palm oil mill is generated the vast amount of EFB, shell and fiber; each waste can be utilized to produce renewable energy. The EFB utilization was compared in five scenarios and the scenario of use EFB for mulching in term of cost, environment, and energy. The five scenarios of the EFB utilization were developed for the effective use of EFB as energy resource, which EFB was used as a solid fuel to produce electricity in new installing of CHP plant with the optimizing of location in Malaysia. The results showed that the scenario case E, which the case of installing of CHP plant on the amount of EFB availability, was the most benefit case for using EFB as an energy source. There are most profit 8.73 million US$/year, net CO_2 avoided emission 128,270 ton CO_2/year, and energy saving 780 TJ/year. Shell and fiber alone can be generated more than enough energy to meet the energy demand of the palm oil mill. The typical palm oil mill released the excess heat 24.2 MJ/ton FFB, which possible to use for EFB pre-treatment before use EFB as solid fuel to produce electricity. The results showed that EFB can be used as fuel for CHP plant in Malaysia for gaining the most profit, net CO_2 avoided emission, and most energy saving, which can be applied to another countries for optimizing the palm oil wastes as renewable energy.

The choices of the effective use of palm oil waste concerning the benefits economic, which are cost and profit, environmental, and energy, which they are the scope of the system analysis and the importance weight of each benefit will be depended on the selector's policy.

Pepatung et al., [29] studied the alternative utilization of biogas from a treatment plant of pig and food SME wastewater in central Thailand. The biogas was generated from pig and food wastewater treatment plant. There are H-UASB and constructed wetland. The estimated biogas production was approximately to 7,000 m^3/d. The biogas was content of 60% for methane composition. The biogas utilization was approached into 2 parts. First, the biogas was used for the substitution inform of thermal energy, and produced electricity inside the treatment plant. Second, the biogas was used for the remaining biogas for the energy supply in form of electricity to the local communities. The finance evaluation was used in this study for the most benefit of the biogas utilization part. The initial biogas utilization was used as a directly renewable fuel for heat production. The heat was used as a source of energy. Figure 2.5 shows the biogas utilization guidelines. There are two majors group of biogas utilization. The choice of project was suggested by two major types. There are financial analysis and economic analysis. The financial analysis is the analyzed the piquancy of the project and reported the results to an investment, as a project selector. The economic analysis is the analyzed the benefit, which effected to the country’s economic, of project investment. Both analyses were calculated from cash flow, but the economic analysis was investigated from tax, interest, and externalities [29].

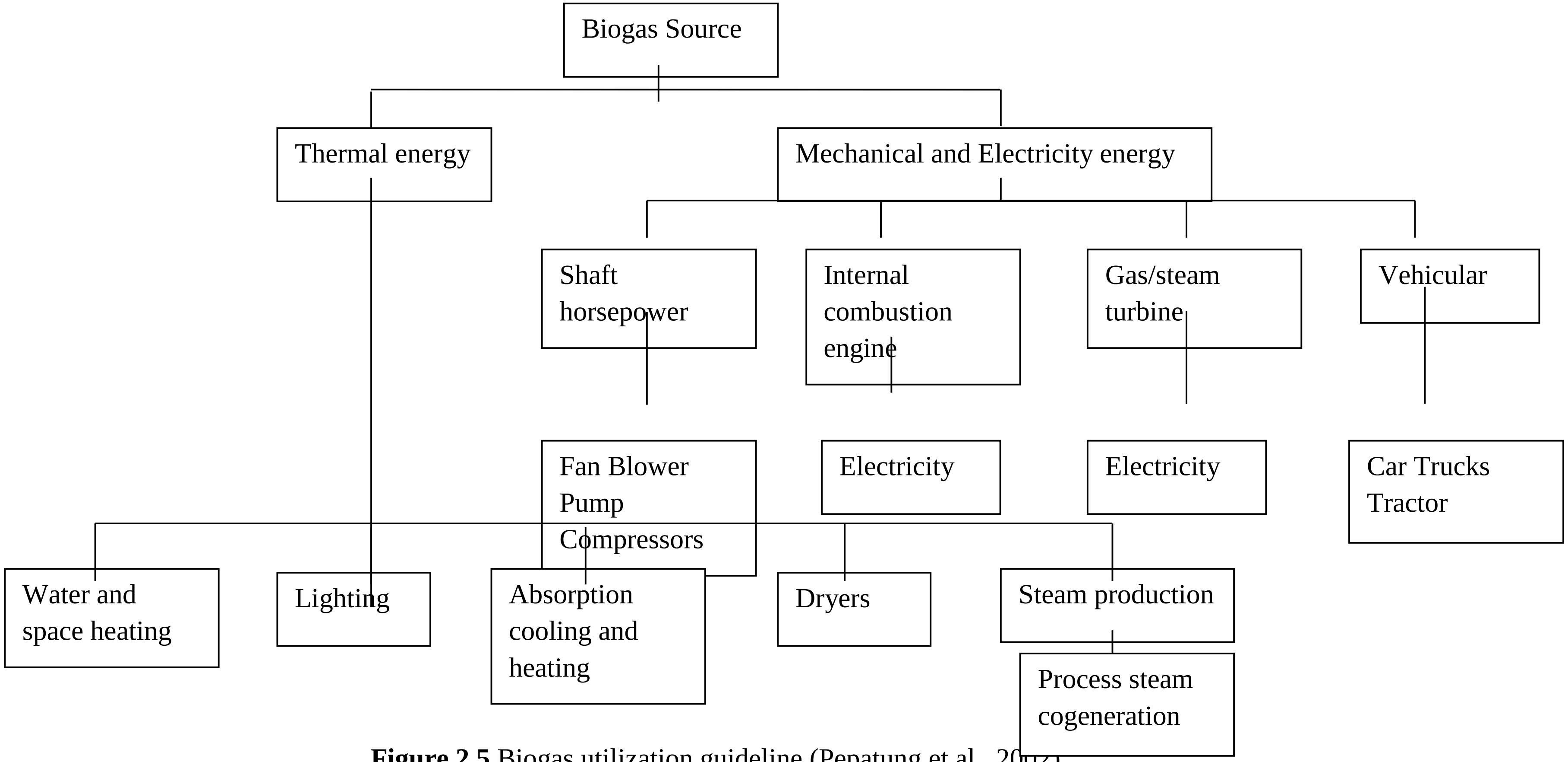

Figure 2.5 Biogas utilization guideline (Pepatung et al., 2002)

2.6.1 Greenhouse gas emissions

Greenhouse gas emissions (GHG) were used for environmental analysis. The amount of GHG emission was demonstrating the treatment reactor performance in term of environment. GHG are those gaseous constituents of atmosphere that effected to the thermal infrared radiation. In the Earth's atmosphere, the primary GHG are water vapor (H_2O), carbon dioxide (CO_2), Nitrous oxide (N_2O), methane (CH_4), and ozone (O_3The measurement of GHG emission was reported in term of global warming potential (GWPs). The GWPs was the amount of GHG in reference gas, which is CO_2. The relationship between gas and CO_2 equivalent was shown in Table 2.11.

Table 2.11 Global warming potential (GWP) and atmosphere lifetime [30]

Gas	Atmosphere lifetime	100-year GWP[a]	20-Year GWP	500-year GWP
CO_2	50-200	1	1	1
CH_4[b]	12±3	25	56	6.5
N_2O	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	400
C_6F_{14}	3,200	7,400	5,000	10,700
SF_6	3,200	23,900	16,300	34,900

[a] GWPs used here are calculated over 100 year time horizon

[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO2 is not included.

Wastewater can be a source of methane (CH_4) when treated or disposed anaerobically as well as carbon dioxide (CO_2). For industrial wastewater, GHG emissions from the treatment processes were calculated by using the GHG estimation equation from IPCC [30] as shown below:

$$\mathrm{CH_4\ emissions} = \sum_{\mathrm{i}} \mathrm{Q} \times \mathrm{COD_{removaed}} \times \mathrm{B_o} \times \mathrm{MCF} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

Where:

CH_4 emissions = CH_4 emissions in inventory year, kg CH_4/yr

Q = wastewater generated, m^3/yr

$COD_{removed}$ = industrial degradable organic component in wastewater, kg COD/m^3

Bo = maximum CH_4 producing capacity, kg CH_4/kg COD

MCF = methane correction factor (fraction) (Table 2.12)

Table 2.12 Default values for methane correction factor and biomass yield [30]

Treatment System	MCF[a]	λ
Wastewater Treatment Processes		
Aerated treatment process (e.g., activated sludge system), well managed	0	0.65
Aerated treatment process, overloaded (anoxic areas)	0.3	0.45
Anaerobic treatment process (e.g., anaerobic reactor)	0.8	0.1
Facultative lagoon, shallow (< 2 m deep)	0.2	0
Facultative lagoon, deep (≥ 2 m deep)	0.8	0

The amount of CH_4 emissions can be used as the global warming potential as CO2 equivalent by 1 kgCH_4 was 25 kgCO_2 equivalents. The efficiency of GHG emission reduction was the importance index for the environmental analysis.

2.6.2 Energy from biogas

Anaerobic biological wastewater treatment produced biogas as a source of renewable energy. The heating value of biogas, which content 60-70% of methane, was shown in the Table 2.13. The heating value of methane gas was referring to the energy value of biogas. The total of energy production from biogas was used for energy analysis.

Table 2.13 Heating values of common fuels [31]

Fuel	Heating value		
	MJ/kg	MJ/m^3	kWh/kg
Hydrogen	141.8	13.00	39.4
Methane	55.5	39.40	15.42
Gasoline	47.3	-	13.14
Natural gas (US)	37.9	-	18.53
Carbon monoxide	10.11	-	2.80

CHAPTER 3
METHODOLOGY

3.1 Characteristics of wastewater and inoculum seed

Raw POME was collected from a palm oil production plant in Chonburi Province, Thailand. The characteristics of raw POME were determined pH, chemical oxygen demand (COD), oil and grease (O&G), total solid (TS), suspended solids (SS), volatile solids (VS), volatile suspended solids (VSS), total volatile acids (TVA), and alkalinity (Alk). POME characteristics were determined according to the procedures of the Standard Methods of Wastewater Analysis (APHA, 2005). Their characteristics were shown in Table 3.1. There are high in COD (91,800 mg/l), TS (65,845 mg/l), SS (36,470 mg/l), volatile solid in form of TS, SS, and oil and grease (O&G).

Table 3.1 Characteristics of raw POME

Parameters	Value
pH	4.26 ± 0.2
Alk (mg/l)	1,195 ± 0.2
TVA (mg/l)	4,935 ± 0.5
TCOD (mg/l)	91,800 ± 1.5
TS (mg/l)	65,845 ± 1.5
SS (mg/l)	36,470 ± 0.3
VS (mg/l)	57,720 ± 0.1
VSS (mg/l)	23,240 ± 0.1
O&G (mg/l)	19,320 ± 0.1

The inoculum seed was taken from the anaerobic wastewater treatment system of POME under mesophilic condition. The inoculum seed was directly operated under mesophilic condition (35 °C). For thermophilic condition the inoculum seed was acclimatized to thermophilic temperature at 55 °C by start the reactor from room temperature and increase gradually the temperature about 5 °C/day until the temperature 55 °C and the stability parameters were stabled, which were stable in term of pH, TVA, Alk, COD removal, and methane gas production. The characteristics of seed were monitored in term of TS, SS, VS, as well as activity for acidogens and methanogens. Glucose and acetate were used as the substrates for activity analysis of the acidogens and methanogens, respectively. Specific glucose utilization (SGU) and methanogenic activity (SMA) at 55 °C were calculated. Determination of microbial activity was performed using the method of Nopharatana et al. (1998). The microbial activities calculation are shown in Appendix B. High concentration of biomass (VSS) in inoculum seed (77% SS) with activities of acidogens (SGU) and methanogens (SMA) were found at value of 0.72 gCODglucose/gVSS.d and 0.17 gCODmethane/gVSS.d, respectively (Table 3.2). SGU was demonstrated on the glucose consumption rate. SMA was demonstrated on the methane production rate.

Table 3.2 Characteristics of inoculum seed for mesophilic and thermophilic reactors

Parameters	Value	
	Mesophilic reactor	Thermophilic reactor
TS (mg/l)	33,210	33,210
SS (mg/l)	26,100	26,100
TVS (mg/l)	21,050	21,050
VSS (mg/l)	20,085	20,085
SGU ($gCOD_{glucose}$/gVSS.d)	0.77	0.72
SMA ($gCOD_{methan}$e/gVSS.d)	0.27	0.17

3.2 Reactor configuration

Two anaerobic hybrid reactor (AHR) systems of the experiment were set up in a laboratory, as shown in Figure 3.1. AHR is made from acrylic column with a diameter of 9.6 cm. and a height 90 cm. Total volume of 6,000 ml. The working volume of the reactor is 5,800 ml, and working volume was applied by 50% of sludge zone at the bottom of the reactor and 50% of packed zone at the upper of the reactor. The packed zone was contained nylon fibers, which there are the specific surface area 2 m^2/m^3, was installed to the reactors with density of 30 kg/m^3 for microbial attachment as biofilm formation. A silicone tube was installed surrounded outside the reactors for controlling of the reactor temperature. An insulator was covered outside the reactors. Three sampling ports were distributed at different level in AHR. The overall system was contained of AHR, influent and effluent tank, peristaltic pump, gas counter, and water bath as shown in Figure 3.1 and 3.2. The raw POME was fed from storage tank, which storage 4 ºC, crossed water bath for increased the temperature of POME influent at 35 and 55 ºC for mesophilic (MR) and thermophilic (TR) reactors, respectively.

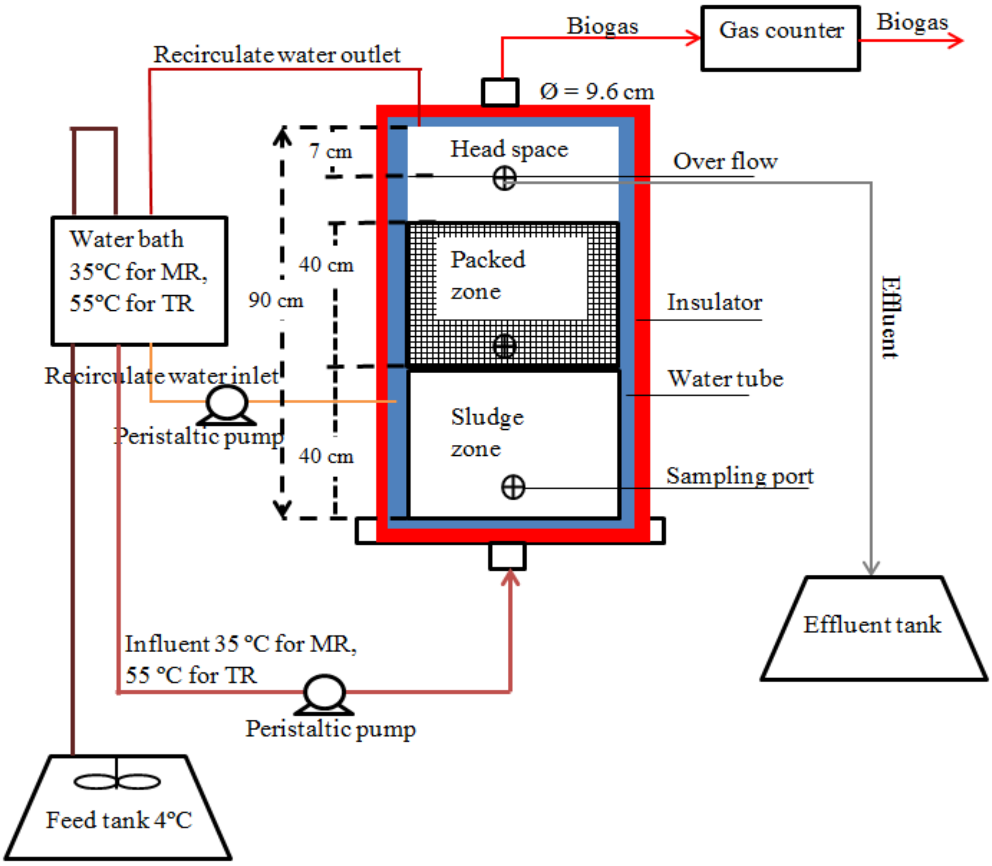

Figure 3.1 Schematic diagram of the AHR system

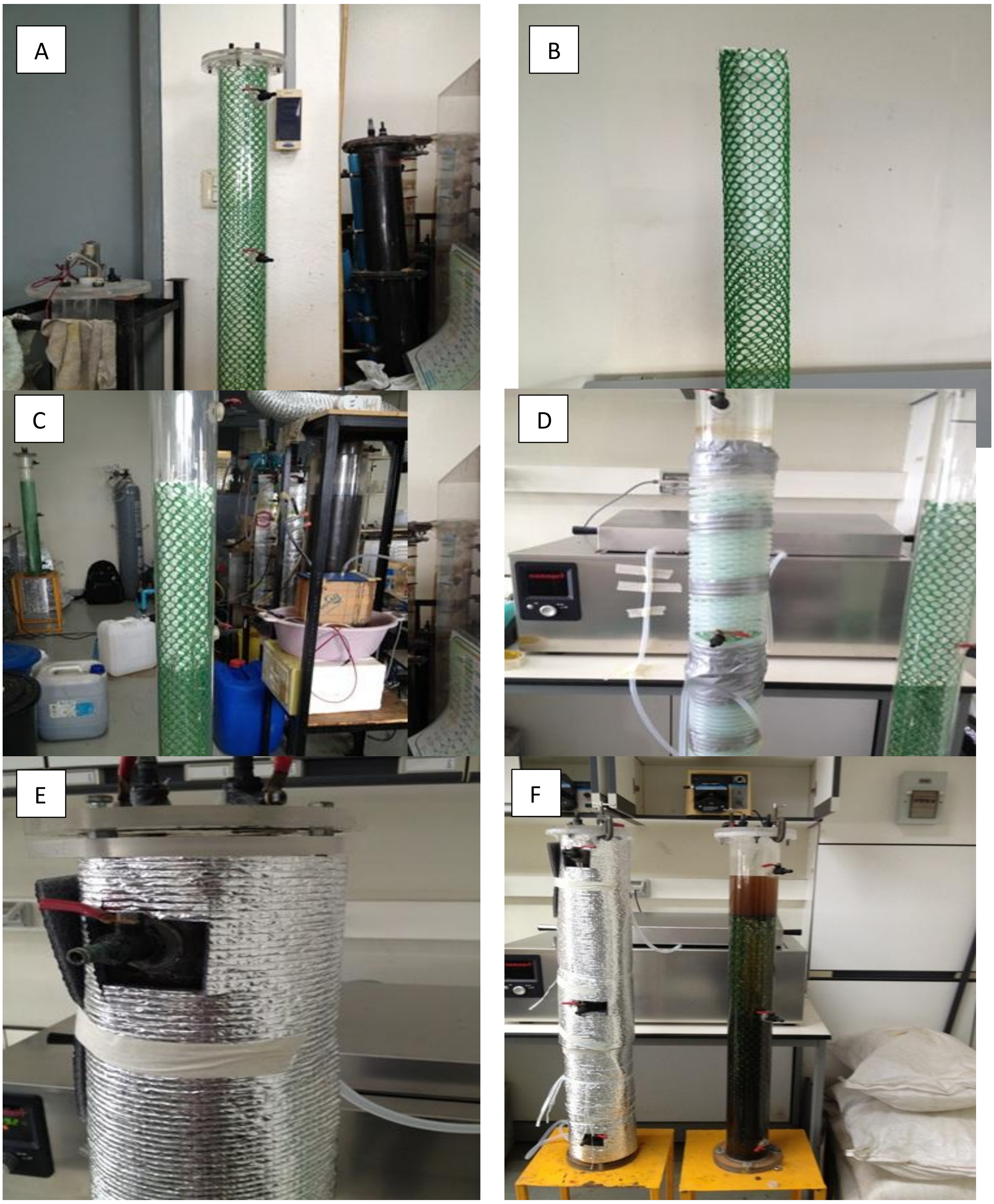

Figure 3.2 (A) cylindrical reactors, nylon fiber for (B) packed zone, (C) packed zone high 40 cm with 30 kg/m^3 of density, (D) temperature control with water bath and water recirculate tube, (E) covered with insulator, (F) reactors with 20 gVSS/l of inoculum seed

3.3 Effect of mesophilic and thermophilic temperatures on reactor performance and stability

Effect of operating temperatures on anaerobic reactors was investigated for two anaerobic reactors, which were mesophilic and thermophilic. The reactors were operated under temperature of 35 °C as a mesophilic condition and temperature of 55 °C as a thermophilic condition. Raw POME was semi-continuously fed upflow from the bottom of sludge bed zone to the packed zone. Figure 3.3 was shown the diagram of the reactor startup and operation of the study. The reactor startup was started from the addition of inoculum seed into the reactors, which was added a half of the reactor’s working volume (20 gVSS/l). The inoculum seed was acclimatized from 35 ºC to 55 ºC with step increasing 5 ºC/day for thermophilic reactor. Next, fill the POME into the reactors at the starting organic loading rate (OLR) of 1.2 gTCOD/l.d and hydraulic retention time (HRT) 20 days, then step increase OLR and reduce HRT until maximum OLR and short HRT condition, which reducing reactors performance and reactors stability were accepted. The operating condition in this study was show in Table 3.3. The mesophilic and thermophilic reactors were operated at temperature of 35 °C and 55 °C, respectively. During reactor startup and operating, the process performances and stability were monitored as well as temperature inside the reactors. All of analysis parameters were compared with two systems. There are reactor performances and stability, microbial activity, and system analysis, which used mesophilic reactor and thermophilic reactors, for determine the maximum benefit at the lowest operating cost, maximum environmental benefit, and energy production from POME treatment, as shown in Figure 3.4.

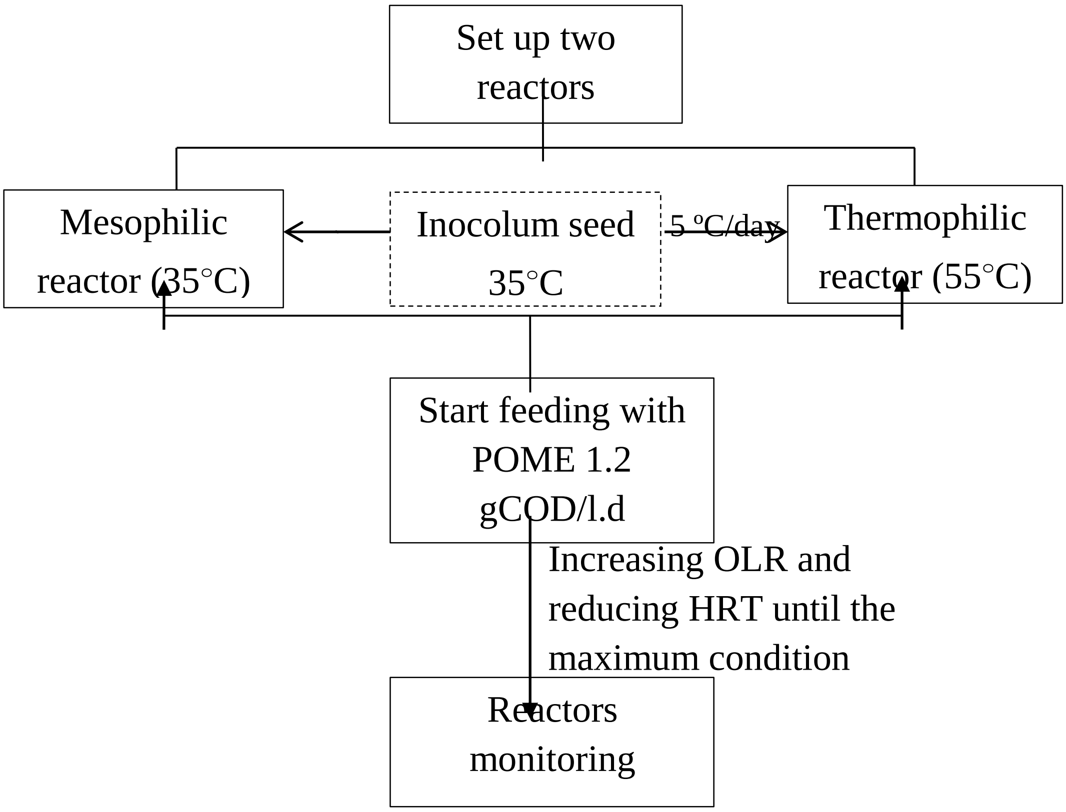

Figure 3.3 The diagram of the reactor startup and operation

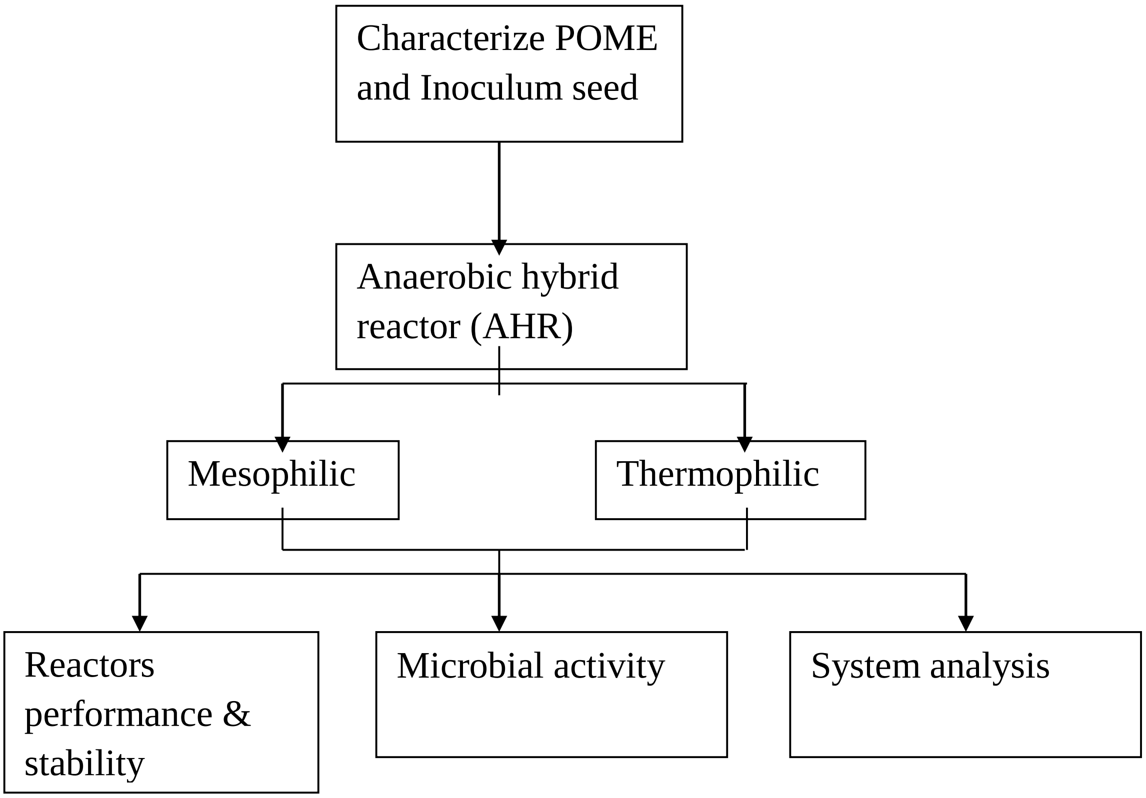

Figure 3.4 Flow diagram of the study

Table 3.3 Operating conditions for MR and TR at various OLR and HRT

Operating period (d)	COD influent (g/l)	OLR (gCOD/l.d)	HRT (days)
1-12	24	1.2	20
13-18	30	2.0	15
19-28	39	2.6	15
29-38	26	2.6	10
39-53	35	3.5	10
54-66	45	4.5	10
67-78	55	5.5	10
79-89	65	6.5	10
90-101	75	7.5	10
102-116	40	7.5	5.3
117-126	45	8.5	5.3
127-136	50	9.5	5.3
137-146	56	10.5	5.3
147-156	61	11.5	5.3
157-162	stop feed		
163-193	75	7.5	10

3.4 Reactor monitoring

The parameters of pH, temperature, COD, alkalinity, TVA and biogas production were measured. The methods for characterization of the effluent are shown in Table 3.4. During startup periods all of parameters were measured every day and after that the parameters were measured, as shown in Table 3.4.

Table 3.4 Methods for characterization of the effluent

Parameter	Analysis Method	Frequency analysis
pH	pH meter	Everyday
Biogas production	Water displacement	Everyday
TVA	Titration method	Everyday
Alkalinity	Titration method	Everyday
TCOD	Close reflux [32]	2 time/week

The determination of microbial activity was carried out in triplicate using 120 mL vials with 100 mL of working volume. The substrate (F)-inoculum (M) ratio (F/M) in the final volume was 0.1gCOD/gVSS. Glucose and acetate were used as the substrates for activity analysis of the acidogens (SGU) and methanogens (SMA), respectively. Determination of microbial activity was performed using the method of Nopharatana et al., [33]. The microbial activities of the sludge and packed zones in AHR, the suspended sludge samples from the sludge zone and the attached biofilm samples fromthe supporting media in the packed zone were collected and determined SS, VSS and microbial activities at the OLR of 3.5, 5.5, 7.5, and 11.5 gCOD/l.d. The temperature inside the reactors were monitored 2-3 time/week by collected the sampling water inside the reactors from three sampling ports.

3.5 System analysis

The performance of anaerobic digestion wastewater treatment was investigated overall treatment system, which included energy production, wastewater treatment, and costs of investment and operation of the system. In this study was focused on the thermophilic and mesophilic treatment systems. The systems were studied on assumption of plant scale and operated with best performance condition. Figure 3.5 shows the diagram of system analysis. The consideration of system analysis was started with system design, which is sizing the reactors from laboratory scale to plant scale based on high capacity with maximum OLR and shortest HRT with high performance and stability of the systems, and also design other equipment requirement for operating the systems. Next, calculation the information from the system design for output data, which are finance, environment, and energy. The output information from the period step was analyzed on system analysis for export the results, which are the highest benefit of finance, environmental, and energy. The results were suggested for the systems selection with highest benefit of the system performance.

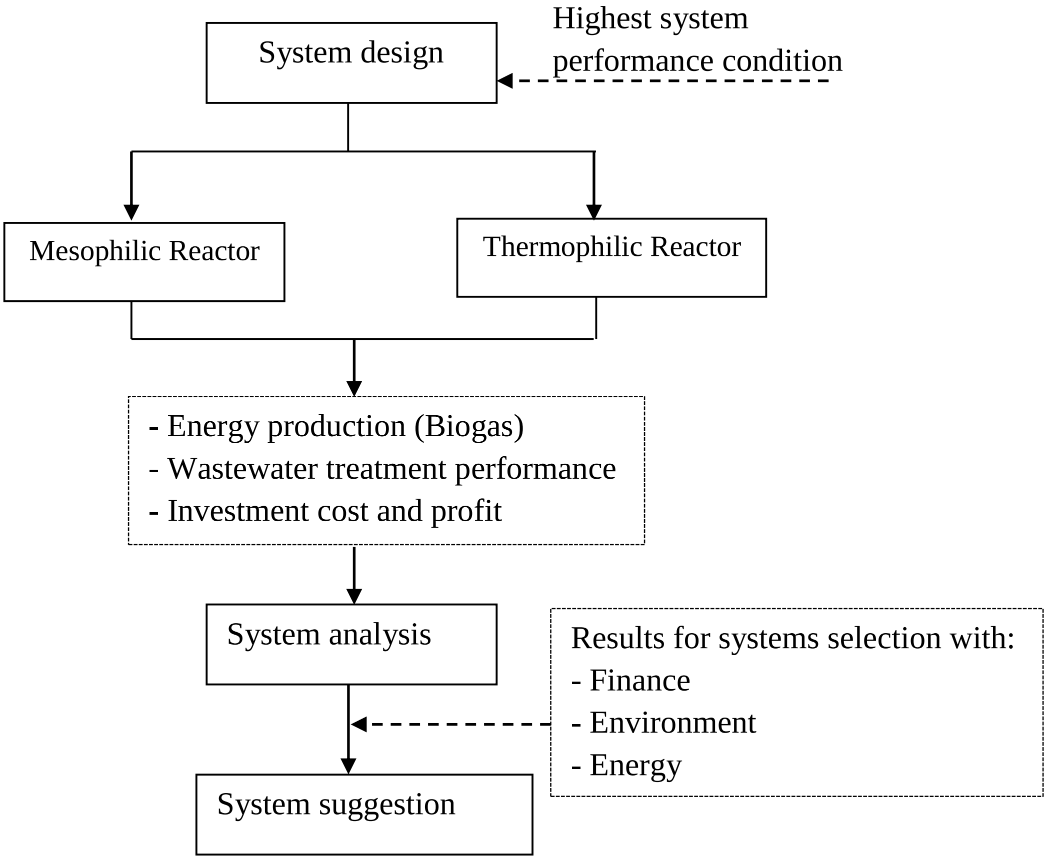

Figure 3.5 Diagram of system analysis

3.5.1 Financial analysis

Financial analysis was investigated for investment cost and annual operating and maintenance (O&M) costs of the mesophilic reactor (MR) and thermophilic reactor (TR) treatment plants. Annual profit was come from electricity sell, which produced from biogas production of the systems, included the cost of annual operating and maintenance as well. Financial analysis was investigated on payback period (PP), net present value (NPV), and internal rate of return (IRR), by suggest the system, which consist of shortest of PP, highest of NPV, and IRR, to interesting system (Figure 3.6). The diagram of financial analysis and procedure of PP, NPV, and IRR calculation were shown below [34]

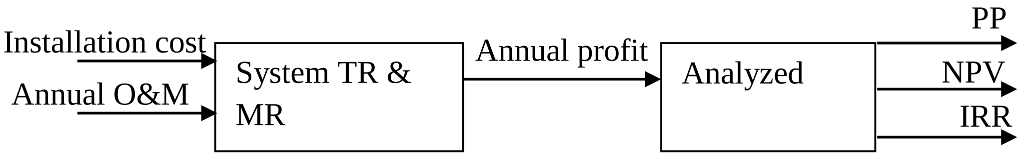

Figure 3.6 Financial analysis

3.5.1.1 PP equation

$$\text{PP (yr)} = \frac{\text{Installation cost}}{\text{Annual profit}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.1)$$

3.5.1.2 NPV equation

$$\text{NPV} = \sum_{n=0}^{N} \frac{\text{NCF}_n}{(1+i)^n} - \text{TIC} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.2)$$

Where;

TIC = Total installation cost (Baht)

NCF_n = Net cash flow of year n (Baht/yr)

i = Discount rate

N = Number of years in the life of the project

3.5.1.2 IRR equation

IRR is the value of “i” in equation (2) at NPV equal zero.

$$\text{NPV} = \sum_{n=0}^{N} \frac{\text{NCF}_n}{(1+i)^n} - \text{TIC} = 0 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.3)$$

3.5.2 Environmental analysis

Environmental analysis was conducted on the total organic waste degradable performance of mesophilic and thermophilic reactors, and the performance of greenhouse gas (GHG) emissions reduction of the mesophilic and thermophilic reactors as well. The system boundary was shown in Figure 3.7. The system boundary was divided into two scenarios. The first scenario was the case of the utilization of biogas, which used for electricity production. The second scenario was the case of without the utilization of biogas.

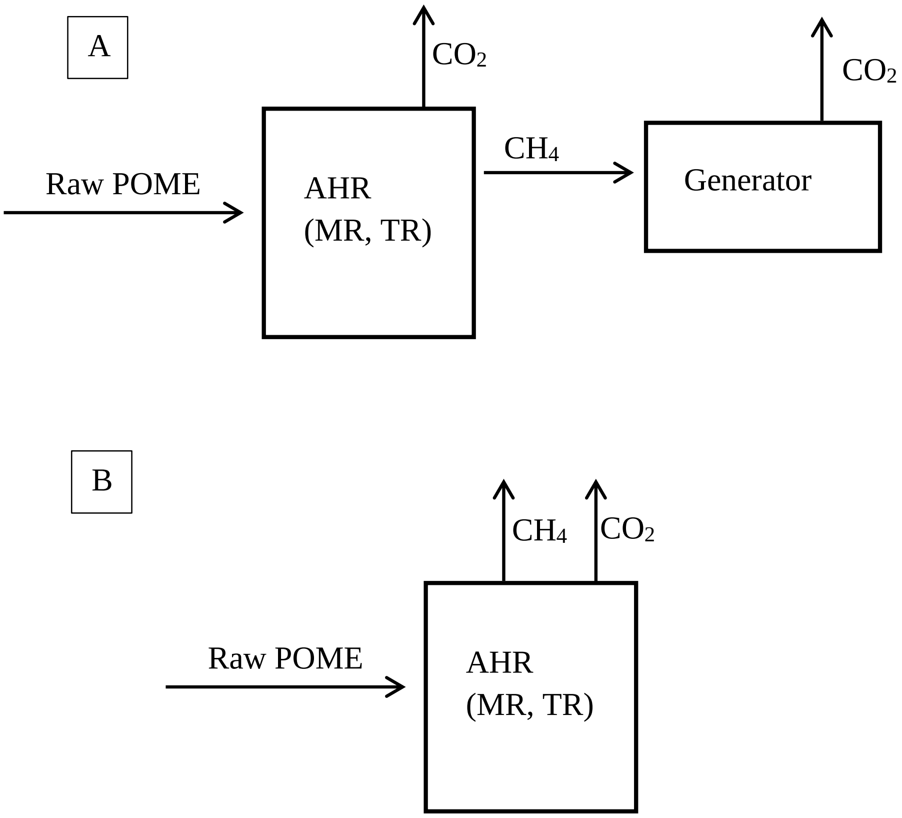

Figure 3.7 System boundary of POME treatment with mesophilic and thermophilic AHR for GHG emissions analysis, scenario 1; reactor with biogas utilization (A), scenario 2; reactor without biogas utilization (B)

The degradation of POME was analyzed by using the equation [35] as follows:

$$\mathrm{TOW_{ind}}\left(\frac{\mathrm{kgCOD}}{\mathrm{yr}}\right) = \mathrm{Q_{POME}} \times \mathrm{D_{ind}} \times \mathrm{DS_{ind}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3.4)$$

Where;

$\mathrm{TOW_{ind}}$ = Total industrial organic wastewater removal (kg COD/ yr)

$\mathrm{Q_{POME}}$ = Wastewater generation (m^3/ yr)

$\mathrm{D_{ind}}$ = Industrial organic components (kg COD/ m^3 wastewater)

$\mathrm{DS_{ind}}$ = Fraction of industrial degradable organic components, removed as sludge and biogas

The amount of GHG emissions from biogas production for Scenarios 1 and 2 were investigated from the results of methane and carbon dioxide gas productions of this study. The results were analyzed and compared to the GHG emissions from calculation of IPCC equation for industrial wastewater ([30] as shown in the equation below:

IPCC equation for estimated GHG emissions

$$\mathrm{GHG_{biogas}} = \mathrm{GHG_{CH_4}} + \mathrm{GHG_{CO_2}} \ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots(3.5)$$

$$\mathrm{GHG_{CH_4}} = \mathrm{CH_4\ production} \times \rho_{\mathrm{CH_4}} \times \mathrm{GWP\_CH_4} \ldots\ldots\ldots(3.6)$$

$$\mathrm{GHG_{CO_2}} = \mathrm{CO_2\ production} \times \rho_{\mathrm{CO_2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.7)$$

Where:

$\mathrm{GHG_{biogas(i)}}$ = GHG emissions from biogas production process (tonCO_{2e}/yr)

$\mathrm{GHG_{CH4(i)}}$ = GHG emission from CH_4 emissions from biogas production process (tonCO_{2e}/yr)

$\mathrm{GHG_{CO2(i)}}$ = GHG emission from CO_2 emissions from biogas production process (tonCO_2/yr)

CH_4 production = Volume of CH_4 production (m^3/yr)

CO_2 production = Volume of CO_2 production (m^3/yr)

$\rho_{\mathrm{CH_4}}$ = Density of methane gas (kgCH_4/m^3)

$\rho_{\mathrm{CO_2}}$ = Density of carbon dioxide gas (kgCO_2/m^3)

GWP_CH_4 = Global warming potential of methane (kgCO_{2e}/kgCH_4)

Equation for estimated GHG emissions from this study

$$\mathrm{GHG}_{\mathrm{biogas}\,(i)} = \mathrm{GHG}_{\mathrm{CH_4}(i)} + \mathrm{GHG}_{\mathrm{CO_2}(i)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

$$\mathrm{GHG}_{\mathrm{CH_4}(i)} = \mathrm{Q_{POME}} \times \mathrm{COD_{removal}} \times \mathrm{Bo_{CH4}} \times \mathrm{MCF} \times \mathrm{GWP\_CH_4} \ldots\ldots (3.9)$$

$$\mathrm{GHG}_{\mathrm{CO_2}(i)} = \mathrm{Q_{POME}} \times \mathrm{COD_{removal}} \times \mathrm{Bo_{CO2}} \times \mathrm{MCF} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

Where:

$\mathrm{GHG_{biogas(i)}}$ = GHG emissions from biogas production process ($\mathrm{tonCO_{2e}}$/yr)

$\mathrm{GHG_{CH4(i)}}$ = GHG emissions from CH_4 emissions from biogas production process ($\mathrm{tonCO_{2e}}$/yr)

$\mathrm{GHG_{CO2(i)}}$ = GHG emissions from CO_2 emissions from biogas production process ($\mathrm{tonCO_2}$/yr)

$\mathrm{Q_{POME}}$ = Volume of POME generation (m^3/year)

$\mathrm{Bo_{CH4}}$ = CH_4 unit of organic compounds ($\mathrm{kgCH_4/kgCOD}$)

$\mathrm{Bo_{CO2}}$ = CO_2 unit of organic compounds (kg $\mathrm{CO_2/kgCOD}$)

MCF = Methane conversion factor of AHR

$\mathrm{GWP\_CH_4}$ = Global warming potential of methane ($\mathrm{kgCO_{2e}/kgCH_4}$)

The GHG emissions from electricity production was approximated by using the Equation (3.8) and the GHG emission factor for electricity production with biogas as a fuel

$$\mathrm{GHG_{electricity}} = \text{Electricity production } \times 0.524 \ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

Where;

$\mathrm{GHG_{electricity}}$ = GHG emissions from generator ($\mathrm{tonCO_{2e}}$/yr)

Electricity production

= Electricity production from biogas (MWh/yr)

0.527 = GHG emission factor for electricity production from biogas ($\mathrm{toneCO_{2e}}$/MWh)

3.5.3 Energy analysis

Energy analysis was investigated for energy and electricity production from the systems. There are biogas productions from mesophilic and thermophilic POME treatment systems and electricity production from this biogas. In the palm oil production periods, POME was generated from palm oil production processes at the temperature of 80 – 90 ºC, the utilization of this point was used. Therefore, the energy requirement for reactor temperature controlling was not necessary for both treatment plants. There are required only cooling pond for the temperature cool down. Typically, palm oil production plant was shut down production processes in 2-3 months in 1 year. Thermophilic treatment plant was required the energy for heating the temperature inside the reactor to stable at 55 ºC in this time. For energy analysis, this energy requirement for thermophilic reactor was calculated. This energy requirement was less effective to the energy balance of thermophilic reactor. The energy analysis was analyzed on assumption of all of biogas production from the treatment unit will be used as a fuel to produced steam for electricity production. However, there are many ways of biogas utilization as shown in Figure 2.5.

CHAPTER 4
RESULTS AND DISCUSSION

Thermophilic and mesophilic anaerobic hybrid reactors (AHRs) were operated for 193 days consecutively by increasing the organic loading rate (OLR) and decreasing hydraulic retention time (HRT). The operating times for each condition in this study was done in the short period to fasten the reactor start up for the maximum OLR and shortest HRT. During the operation period, the determination of the flexibility and capability of AHRs to treat and produce methane from POME at various OLR and HRT were studied on reactor performance and stability including system analysis. The reactors were operated by increasing OLR from 1.2 gCOD/l.d to 11.5 gCOD/l.d and decreasing HRT from 20 days to 5.3 days at high temperature condition (thermophilic 55°C) and lower temperature condition (mesophilic 35 °C). Raw POME, which the characteristics were shown in Table 3.2, was fed into the reactor; started with COD concentration of 24,000 mg/l (OLR 1.2 gCOD/l.d at 20 d HRT) and increased stepwise to 60,000 mg/l (OLR 11.5 gCOD/l.d at 5.3 d HRT). Fifteen operating conditions of AHR at OLR 1.2 gCOD/l.d with 20 d HRT (OLR 1.2 HRT 20), OLR 2.0 gCOD/l.d with 15 d HRT (OLR 2.0 HRT 15), OLR 2.6 gCOD/l.d with 15 d HRT (OLR 2.6 HRT 15), OLR 2.6 gCOD/l.d with 10 d HRT (OLR 2.6 HRT 10), OLR 3.5 gCOD/l.d with 10 d HRT (OLR 3.5 HRT 10), OLR 4.5 gCOD/l.d with 10 d HRT (OLR 4.5 HRT 10), OLR 5.5 gCOD/l.d with 10 d HRT (OLR 5.5 HRT 10), OLR 6.5 gCOD/l.d with 10 d HRT (OLR 6.5 HRT 10), OLR 7.5 gCOD/l.d with 10 d HRT (OLR 7.5 HRT 10), OLR 7.5 gCOD/l.d with 5.3 d HRT (OLR 7.5 HRT 5.3), OLR 8.5 gCOD/l.d with 5.3 d HRT (OLR 8.5 HRT 5.3), OLR 9.5 gCOD/l.d with 5.3 d HRT (OLR 9.5 HRT 5.3), OLR 10.5 gCOD/l.d with 5.3 d HRT (OLR 10.5 HRT 5.3), and OLR 11.5 gCOD/l.d with 5.3 d HRT (OLR 11.5 HRT 5.3) and recovery operated at OLR 7.5 gCOD/l.d and HRT 10 days are shown in Table 4.1. In the initial OLR (OLR 1.2 HRT 20 – OLR 2.0 HRT 15), the reactors was increased intermediately because the increasing of OLR was not effected to the reactors performance and stability as show in section of 4.1 and 4.2. After that, the step increased of OLR and reduced HRT were depended on the steady state of the reactors performance and stability as well as the limitation of raw POME concentrations. The AHRs performance and stability at mesophilic and thermophilic temperature were shown as below, respectively.

Table 4.1 Operating conditions of mesophilic and thermophilic AHRs

Condition	OLR (gCOD/l.d)	HRT (days)	Symbol
1 (12 days)	1.2	20	OLR 1.2 HRT 20
2 (6 days)	2.0	15	OLR 2.0 HRT 15
3 (10 days)	2.6	15	OLR 2.6 HRT 15
4 (10 days)	2.6	10	OLR 2.6 HRT 10
5 (15 days)	3.5	10	OLR 3.5 HRT 10
6 (13 days)	4.5	10	OLR 4.5 HRT 10
7 (12 days)	5.5	10	OLR 5.5 HRT 10
8 (11 days)	6.5	10	OLR 6.5 HRT 10
9 (12 days)	7.5	10	OLR 7.5 HRT 10
10 (15 days)	7.5	5.3	OLR 7.5 HRT 5.3
11 (10 days)	8.5	5.3	OLR 8.5 HRT 5.3
12 (10 days)	9.5	5.3	OLR 9.5 HRT 5.3
13 (10 days)	10.5	5.3	OLR 10.5 HRT 5.3
14 (10 days)	11.5	5.3	OLR 11.5 HRT 5.3
stop feeding 5 days for reactor recovery			
15 (41 days)	7.5	10	OLR 7.5 HRT 10

4.1 Reactor performance and stability of AHR at mesophilic temperatures

A mesophilic anaerobic reactor was successfully operated with fifteen operating conditions within 193 days. The reactor temperature was controlled at 35±3 °C. The process performance and stability were investigated at each operating condition. The microbial activities of non-methanogens (SGU) and methanogens (SMA) were interval assayed. The overall process performance and stability were monitored, while microbial activity was monitored at sludge zone and packed zone.

4.1.1 Reactor stability

The reactor stability was demonstrated in terms of pH, TVA, Alk, and TVA/Alk. The results of the reactor stability at each operating condition are shown in Figures 4.1 and 4.2. The pH of mesophilic reactor was constant 7.5 – 7.8 with the condition of OLR 1.2 HRT 20 to OLR 7.5 HRT 10, after that pH was decreased from 7.36 to 6.66 at OLR 7.5-11.5 HRT 5.3. Alk was started from 2,560 mg/l at OLR 1.2 HRT 20 and slightly increased with the increasing of OLR, until maximum with 4,090 mg/l at OLR 7.5 HRT 10. After that Alk was decreased, once the end of processed operation at OLR 11.5 HRT 5.3, the Alk was 2,630 mg/l. TVA was started from 1,085 mg/l at OLR 1.2 HRT 2.0 and slightly increased with the increasing of OLR, until maximum with 2,830 mg/l at OLR 11.5 HRT 5.3. After that TVA was decreased, once the end of processed operation at OLR 7.5 HRT 10, the TVA was 1,080 mg/l. For ratio of TVA/Alk was constant with 0.4 – 0.5 at the condition of OLR 1.2 HRT 20 to OLR 7.5 HRT 10, after that it was increased until maximum at OLR 11.5 HRT 5.3 with 1.06. At the initial stage, which in OLR 1.2 HRT 20 to 7.5 HRT 10, pH was slightly stable, the TVA of the reactor was increased in relation to the increasing of OLR and was increased step with higher OLR was fed into the reactor, while Alk was increased within OLR 1.2 HRT 20 to OLR 7.5 HRT 10 and decreased after these condition. It was effected from an accumulation of organic acid in the reactor. At higher OLR and shorter HRT, which since OLR 7.5 HRT 5.3 to OLR 11.5 HRT 5.3, TVA was increased closely higher than Alk, this effected to TVA/Alk was higher than normal environmental inside the reactor condition.

According to the process stabilities of the mesophilic reactor, the increasing of OLR mean the increasing of organic compounds, when the organic compounds was more fed into the process, the process as well as produced more organic acid substrate, that effected to the pH was decreased at high OLR feeding. Notice, since OLR 7.5 HRT 5.3, pH was decreased. The decreasing of pH was affected from the organic acid substrate accumulation, observed by the increasing of TVA.

Typically, the pH and ratio of TVA/Alk can be used as monitoring process stability [36]. The anaerobic system should be optimized with pH 7 – 8, and TVA/Alk was less than 0.5, which the value of the process was operated without acidification risk [37]. The operating condition of OLR 1.2 HRT 20 to OLR 7.5 HRT 10, the process stability was normal condition for anaerobic digestion. The operating condition of OLR 7.5 HRT 5.3 to OLR 11.5 HRT 5.3, the process stability was signal of failure conditions, which the ratio of TVA/Alk was approximately 1.0. After that AHR was stopped feeding 5 days and was operated with the condition of OLR 7.5 gCOD/l.d and HRT 10 days until the days of 177 the AHR performance and stability were started to stable and closely the performance at the maximum of the period condition of OLR 7.5 gCOD/l.d and HRT 10 days on the days of 101. There are 20 days to recovery to the maximum operating with process performance and stability. These environmental factors will reflect to reactor performance which will illustrate below.

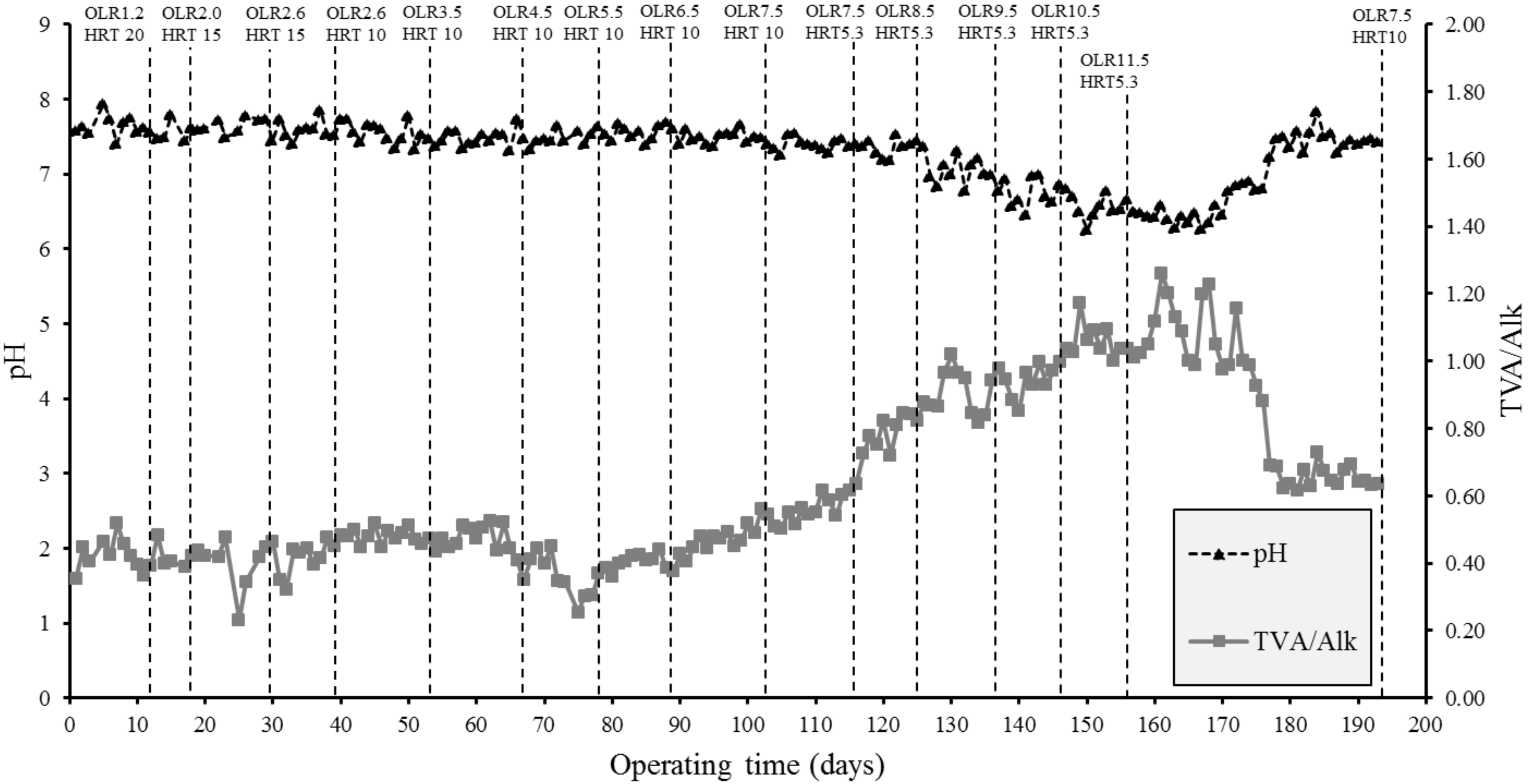

Figure 4.1 pH and ratio of TVA/Alk of mesophilic reactor at various operating conditions

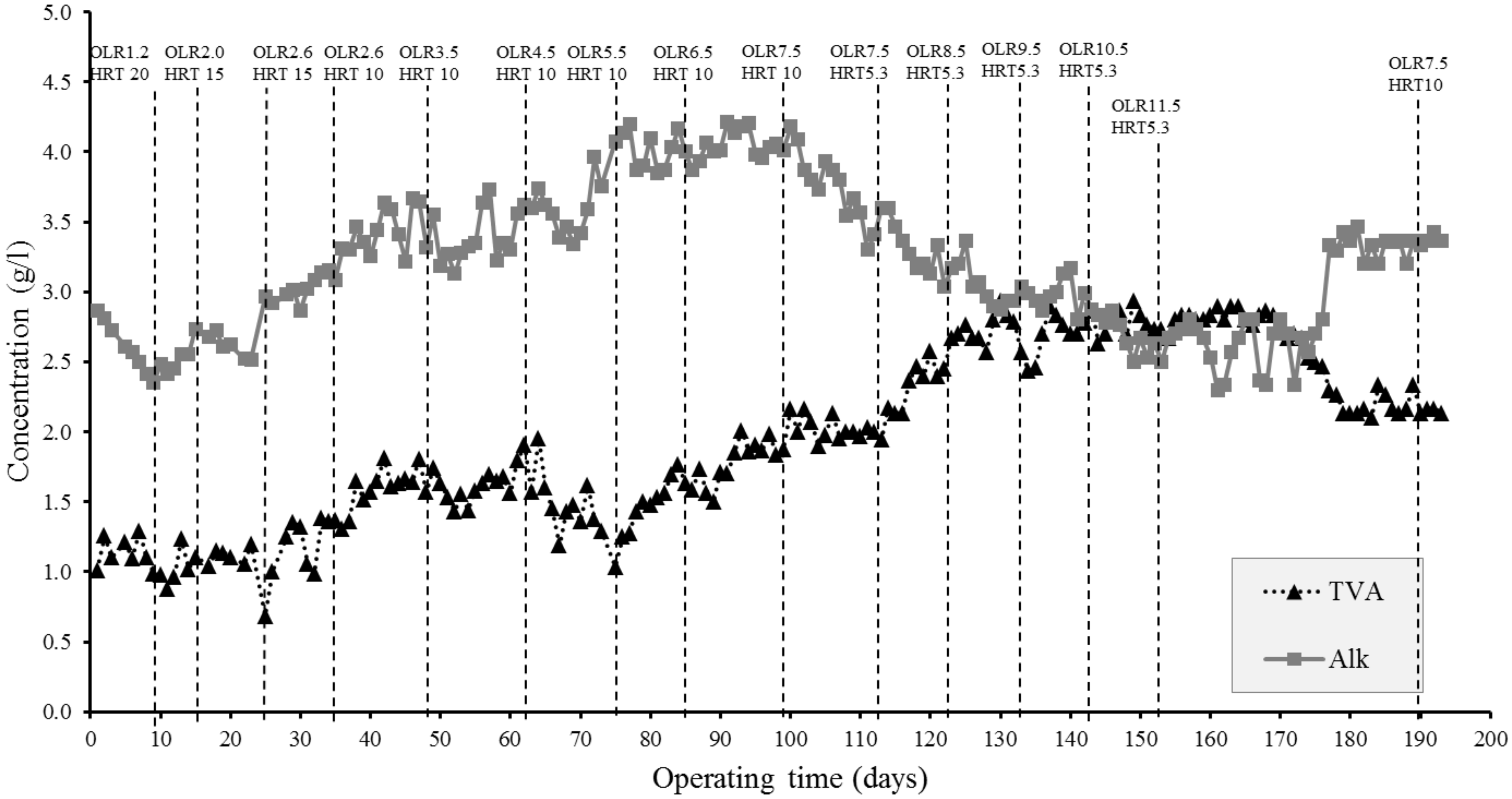

Figure 4.2 Concentration of total volatile acid (TVA) and alkalinity (Alk) from mesophilic reactor at various operating conditions

4.1.2 Reactor performance

The reactor performance was demonstrated in terms of efficiency of COD removal, methane gas production, and methane yield. The results of reactor performance at each operating condition were shown in Figures 4.3-4.5 and Table 4.4. The efficiency of COD removal was observed from 86.89 % at OLR 1.2 HRT 20, and highest at OLR 5.5 HRT 10 with 92.25 %. COD removal at OLR 1.2 HRT 20 to OLR 7.5 HRT 10 with slightly constant 85 – 90 %, while after OLR 7.5 HRT 5.3, COD removal was decreased until oprating reactor to OLR 11.5 HRT 5.3, COD removal was observed minimum at 53.13 %. Methane gas production, which the value of the gas volume at standard temperature (0 ºC) and pressure (100 kPa) condition (STP), was increased with the increasing of OLR, methane gas production was high at OLR 7.5 HRT 5.3-10 with 10.44-12.75 l/d. After OLR 8.5 HRT 5.3, methane gas production was decreased until OLR 11.5 HRT 5.3 was decreased to 5.28 l/d. Methane yield was high at OLR 7.5 HRT 5.3-10 with 0.30-0.35 $lCH_4/gCOD_{removal}$. At the decreasing of HRT was slightly effected to the reactor performance, it was reduced the contact time between the organic substrate, which mixed in the feeding POME, and bacteria in the reactor, after that the constant of HRT, the reactor performance was related with the increasing of OLR.

At the condition of OLR 1.2 to OLR 7.5 gCOD/l.d and HRT 10 days, the rate of the fatty acid conversion to methane with methanogens was closed to the rate of the acid production with acidogens, it can be noticed by less TVA accumulation and high methane production [13]. After that the rate of acid production with acidogens was higher than the rate of the fatty acid conversion with methanogens, these results may be supported from the results of the AHR stability. There are effect of acid accumulation in the AHR was too high, until OLR 11.5 gCOD/l.d HRT 5.3 days, the AHR performance was signal to process failure.

According to the process performance of the mesophilic reactor, the efficiency of COD removal at OLR 1.2 HRT 20 to OLR 7.5 HRT 10, the organic compounds concentration feed (F) was related to the microbial quality and quantity (M). Most of them had degraded within 85 – 90 %. After that the effect of excess organic compounds and accumulation of organic acid production were affected to the reactor performance.

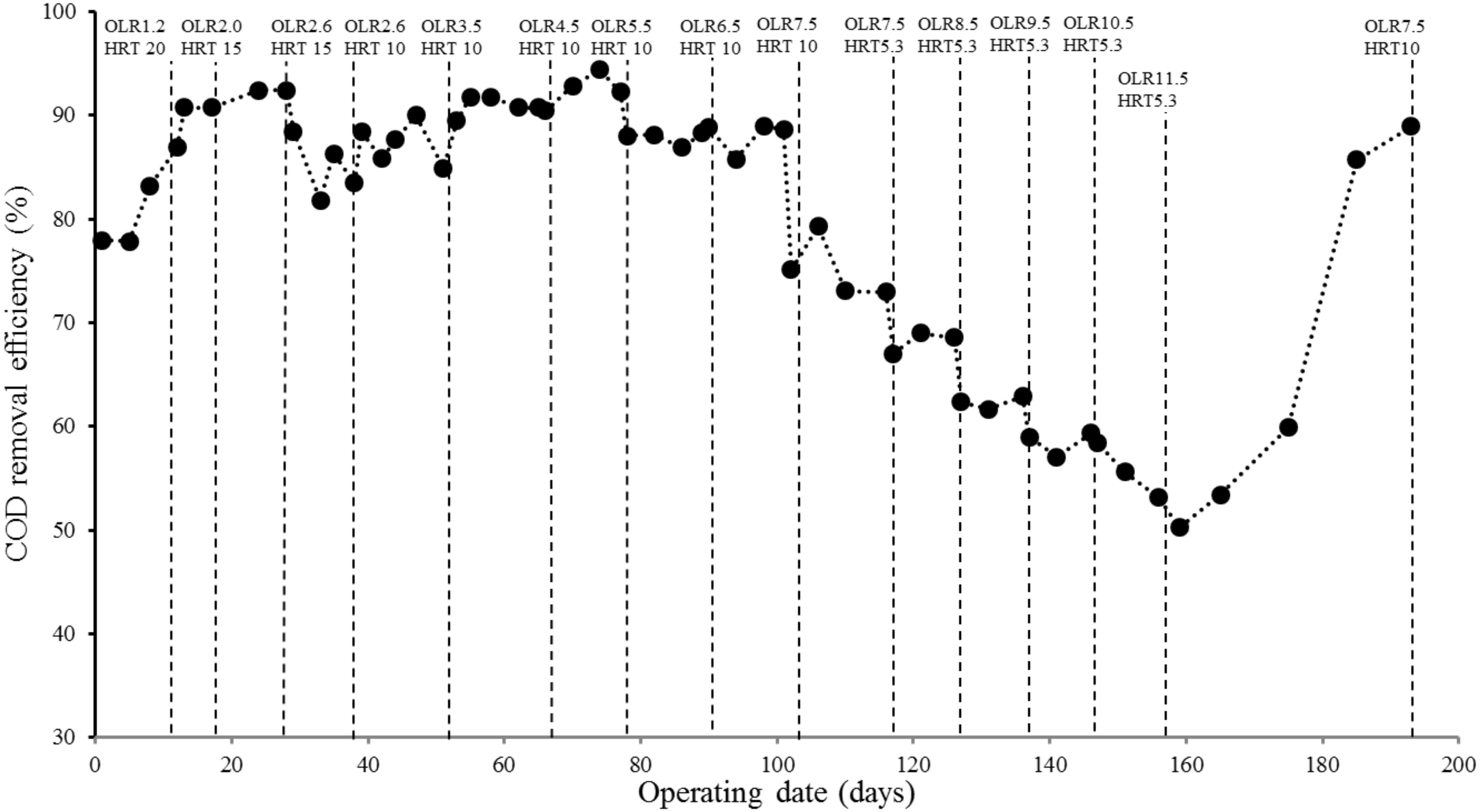

Figure 4.3 Efficiency of COD removal from mesophilic reactor at various operating conditions

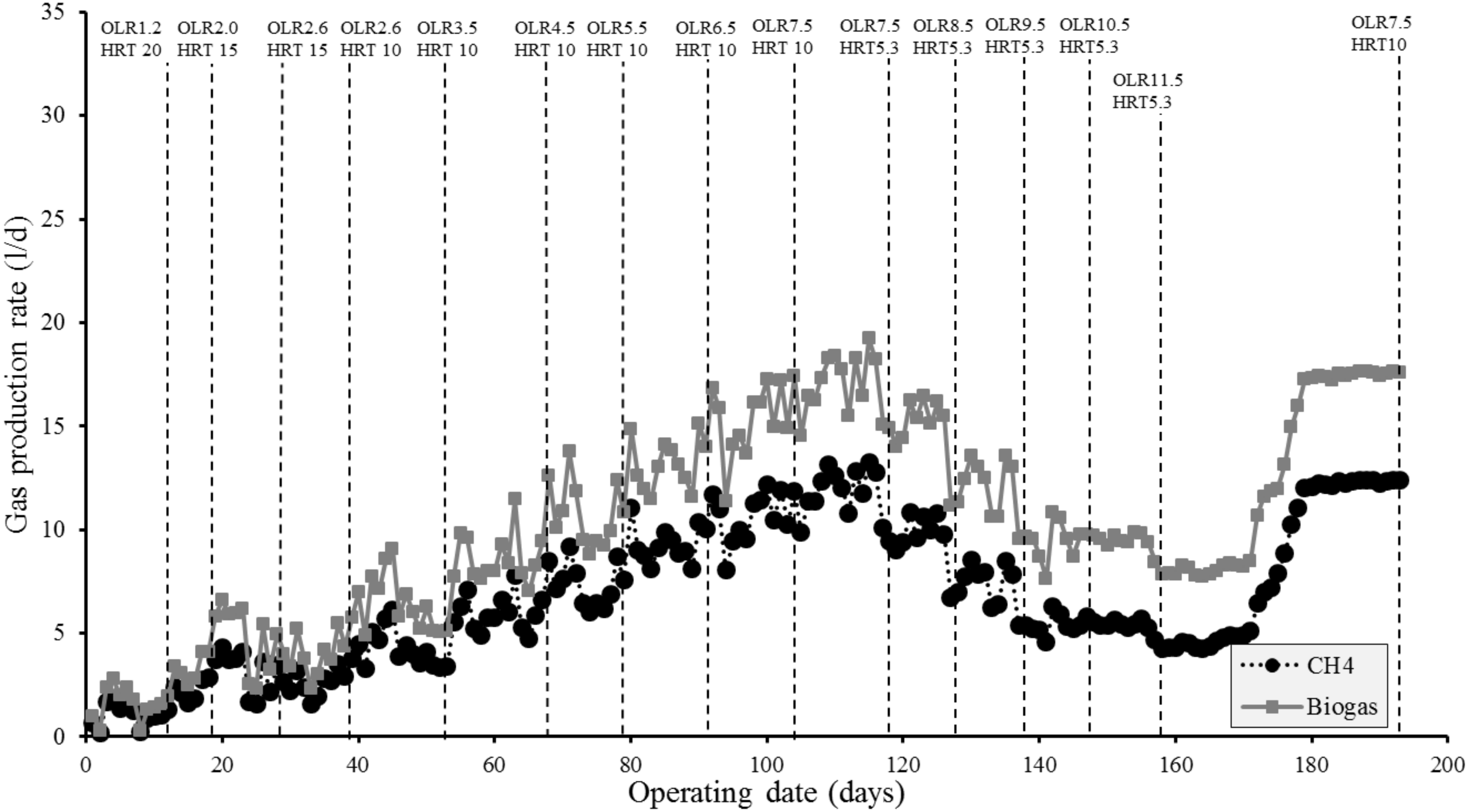

Figure 4.4 Biogas and methane production rate (STP) of mesophilic reactor at various operating conditions

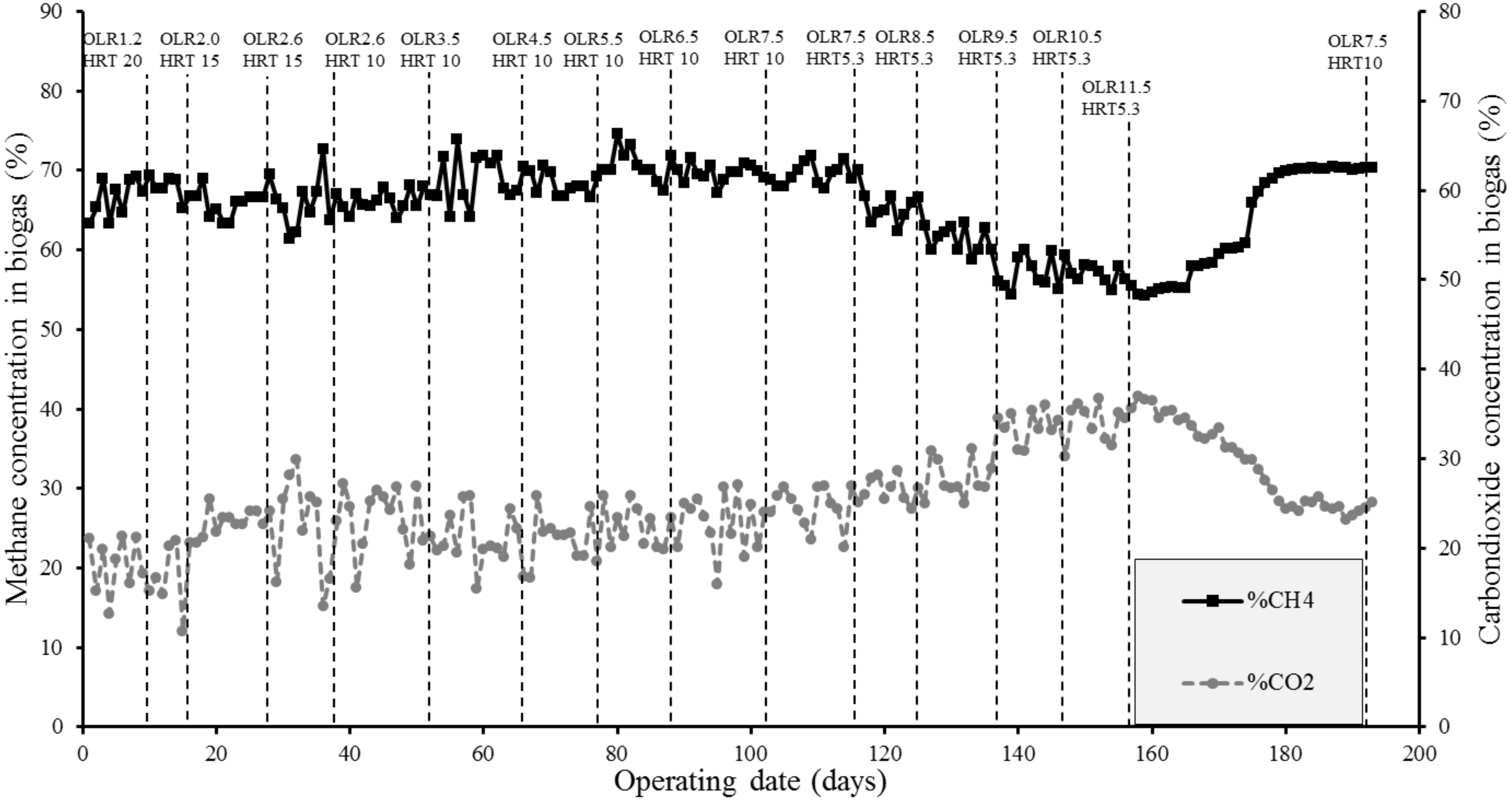

Figure 4.5 Biogas compositions in CH_4 and CO_2 of mesophilic reactor (MR) at various operating conditions

4.1.3 Microbial activities

The microbial activity of the reactor was investigated into 2 terms of SGU and SMA. The activity of the reactor was monitored at sludge zone and packed zone of interval operating conditions, which initial stage, OLR 3.5 HRT 10, OLR 5.5 HRT 10, OLR 7.5 HRT 10, OLR 7.5 HRT 5.3, and OLR 11.5 HRT 5.3. Microbial activities of initial seed for SMA and SGU was 0.26 $gCOD_{methane}$/gVSS.d and 0.77 $gCOD_{glucose}$/gVSS, respectively. At sludge zone, the cell biomass concentration was increased from 20 to 100 gVSS/l with at the initial stage to OLR 7.5 HRT 5.3. After OLR 7.5 HRT 5.3 the cell biomass was decreased to 87.14 gVSS/l at OLR 11.5 HRT 5.3. At packed zone, the cell biomass concentration was increased from 0.00 to 23.78 gVSS/l with at the initial stage to OLR 7.5 HRT 5.3 and after that was decreased to 11.96 gVSS/l at OLR 11.5 HRT 5.3.

By upflow feeding at operating condition HRT 10 OLR 3.5-7.5, it can be noticed that SMA in sludge zone decreased while SGU increased during increase OLR and reduced HRT. On the other hand, SMA and SGU at packed showed increased values. The results of microbial activities of mesophilic reactor were show in Table 4.3. SMA and SGU in sludge zone were in the range of 0.10-0.19 $gCOD_{methane}$/gVSS.d and 1.05-2.59 $gCOD_{glucose}$/gVSS, respectively. SMA and SGU in packed zone were in the range of 0.16-0.25 $gCOD_{methane}$/gVSS.d and 1.35-2.23 $gCOD_{glucose}$/gVSS, respectively.

After over shock load to OLR 11.5 HRT 5.3, total cell biomass was decread as well as SMA and SGU in both zones were decreased due to the reactor failures. These results related to the reactor process (Figure 4.1-4.2) and efficiency of COD removal (Figure 4.3). The SMA was decreased related with the AHR stability, which the increasing of fatty acid accumulated and TVA/Alk ratio >0.4 and pH lower than 7.0. It can be note that, at the condition of OLR 7.5 gCOD/l.d HRT 5.3 days to OLR 11.5 gCOD/l.d HRT 5.3 days, the rate of fatty acid conversion by methanogens was lower than the rate of acid production by acidogens

According to the microbial activity and cell biomass concentrations of the mesophilic reactor, more of the OLR feed into the reactor, the cell biomass concentration was increased in the packed and sludge zones. That effected of the feeding more organic substrate, it mean feeding more bacteria consumption substrate. The cell biomass concentration in the sludge zone was higher than packed zone, because the organic carbon was entranced into the reactor and contact with the microbial at the sludge zone as the first contact and was hydrolyzed into the organic acid and methanogens respectively, at the sludge zone, might be most of non-methanogens. The cell biomass concentration at the packed zone was depended on the packed material efficiency and at the packed zone might be most of methanogens. There are effected to the quality of microbial in the reactor. For SMA at the sludge zone was slightly lower than packed zone, while SGU at the sludge zone was slightly higher than packed zone. The cell biomass concentration was not significant effected to SMA, but effected to SGU. At the sludge zone, the increasing of cell biomass concentration was increased SGU. However, at the packed zone, the increasing of the cell biomass concentration had not increased SGU. It can be noted that most of bacteria at the sludge zone were non-methanogens and at the packed zone was methanogens. The results of SMA was highest at packed zone with 0.25 $gCOD_{methane}/gVSS.d$, which related with the previous study by Meesap., [13] the study of microbial community and suspended solid removal in anaerobic hybrid reactor of palm oil mill effluent with highest SMA at the packed zone about 0.26 – 0.34 $gCOD_{methane}/gVSS.d$. However, the study was founded that the highest SGU was observed at sludge zone with 1.32 – 1.65 $gCOD_{glucose}/gVSS.d$.

The mesophilic reactor performance and stability on POME treatment have been studied in many previous researches. Microbial activity of acidogens and methanogens were affected to the reactor performance and stability. There are many previous studies were shown the mesophilic reactor performance of POME treatment as shown in Table.

Table 4.2 Mesophilic reactor performance for POME treatment in other research studies

Reactor	Waste	OLR (gCOD/l.d)	HRT (days)	COD removal (%)	Methane yield ($l_{CH4}/gCOD_{removed}$)	Reference
AHR (35°C)	POME	7.5	5	80	0.31	Meesap et al., [13]
AHR (37 °C)	POME[a]	15	6.2	87	0.24	Joo-Yound et al., [38]
AHR (35 °C)	POME	7.5	5.3-10	80	0.30-0.35	This research

Note: [a] POME was pre-treated by screw decanter to reduce SS and oil.

Table 4.3 Microbial activities of mesophilic reactor

Condition	Cell biomass concentration		Activity			
	Sludge zone (gVSS/l)	Packed zone (gVSS/l)	SMA ($gCOD_{methane}/gVSS.d$)		SGU ($gCOD_{glucose}/gVSS.d$)	
			Sludge zone	Packed zone	Sludge zone	Packed zone
Initial	20.10	0.00	0.26	0.00	0.77	0.00
OLR 3.5 HRT 10	36.69	16.39	0.11	0.16	1.05	1.35
OLR 5.5 HRT 10	50.22	18.17	0.11	0.23	2.32	2.01
OLR 7.5 HRT 10	109.83	21.11	0.19	0.25	2.59	2.23
OLR 7.5 HRT 5.3	98.45	23.78	0.14	0.23	2.08	2.16
OLR 11.5 HRT 5.3	87.14	11.96	0.09	0.16	1.83	1.94

Table 4.4 Process performance and stability of mesophilic reactor under each operating condition

Condition	OLR (gCOD/l.d)	HRT (Days)	Stability				Performance		
			pH	Alk (mg/l)	TVA (mg/l)	TVA/Alk	COD removal (%)	CH_4 (l/d)	Methane yield ($lCH_4/gCOD_{removal}$)
1	1.2	20	7.63	2,560	1,080	0.42	86.89	1.31	0.16
2	2.0	15	7.58	2,630	1,100	0.42	90.75	2.74	0.17
3	2.6	15	7.76	2,730	1,070	0.39	92.39	3.44	0.30
4	2.6	10	7.60	3,140	1,320	0.42	83.48	2.91	0.24
5	3.5	10	7.55	3,400	1,625	0.48	89.48	3.41	0.24
6	4.5	10	7.46	3,500	1,540	0.44	90.75	4.73	0.29

4.2. Reactor performance and stability of AHR at thermophilic temperatures

The thermophilic anaerobic reactor was successfully operated with fifteen conditions within 193 days. Thermophilic AHR was controlled temperature 55±3 °C. The process performance and stability were monitored with overall process at each condition.

4.2.1 Reactor stability

The reactor stability was investigated for pH, TVA, Alk, and TVA/Alk. The results were shown in Figures 4.6 – 4.7. The pH of the thermophilic reactor was constant at 7.6 – 7.8 with the condition of OLR 1.2 HRT 20 to OLR 7.5 HRT 10, after that pH was decreased from 7.44 to 6.88, with OLR 7.5 HRT 5.3 until OLR 11.5 HRT 5.3. Alk was started from 2,540 mg/l at OLR 1.2 HRT 20 and slightly increased with the increasing of OLR, until maximum with range 3,980 mg/l at OLR 7.5 HRT 10. After that Alk was decreased, once the end of processed operation at OLR 11.5 HRT 5.3, the Alk was 2,460 mg/l. TVA was started from 1,220 mg/l at OLR 1.2 HRT 20 and slightly increased with the increasing of OLR, until maximum with 1,970 mg/l at OLR 7.5 HRT 10. After that TVA was increased, once the end of processed operation at OLR 11.5 HRT 5.3, the TVA was 2,700 mg/l. For ratio of TVA/Alk was constant with 0.4 – 0.5 at the condition of OLR 1.2 HRT 20 to OLR 7.5 HRT 10, after that the ratio of TVA/Alk was increased until maximum at OLR 11.2 HRT 5.3 with 1.10.

According to the process stabilities of the thermophilic reactor, the increasing of OLR was also due to the stability of mesophilic reactor that effected to the pH was decreased at high OLR feeding. Notice, since OLR 7.5 HRT 5.3, the organic acid substrate was accumulated, observed by the increasing of TVA as well as affected to the ratio of TVA/Alk. These results were related with the results of mesophilic reactor.

Therefore, the operating conditions of OLR 1.2 HRT 20 to OLR 7.5 HRT 10, the process stability was the normal condition for anaerobic digestion. The operating condition of OLR 7.5 HRT 5.3 to OLR 11.5 HRT 5.3, the process stability was signal of failure conditions, which the ratio of TVA/Alk was 1.05. After that AHR was stopped feeding 5 days and was operated with the condition of OLR 7.5 gCOD/l.d and HRT 10 days until the days of 171 the AHR performance and stability were stable and closely the performance at the maximum of the period condition of OLR 7.5 gCOD/l.d and HRT 10 days on the days of 100. There are 14 days to recovery to the maximum operating with process performance and stability. These environmental factors will reflect to reactor performance which will illustrate below.

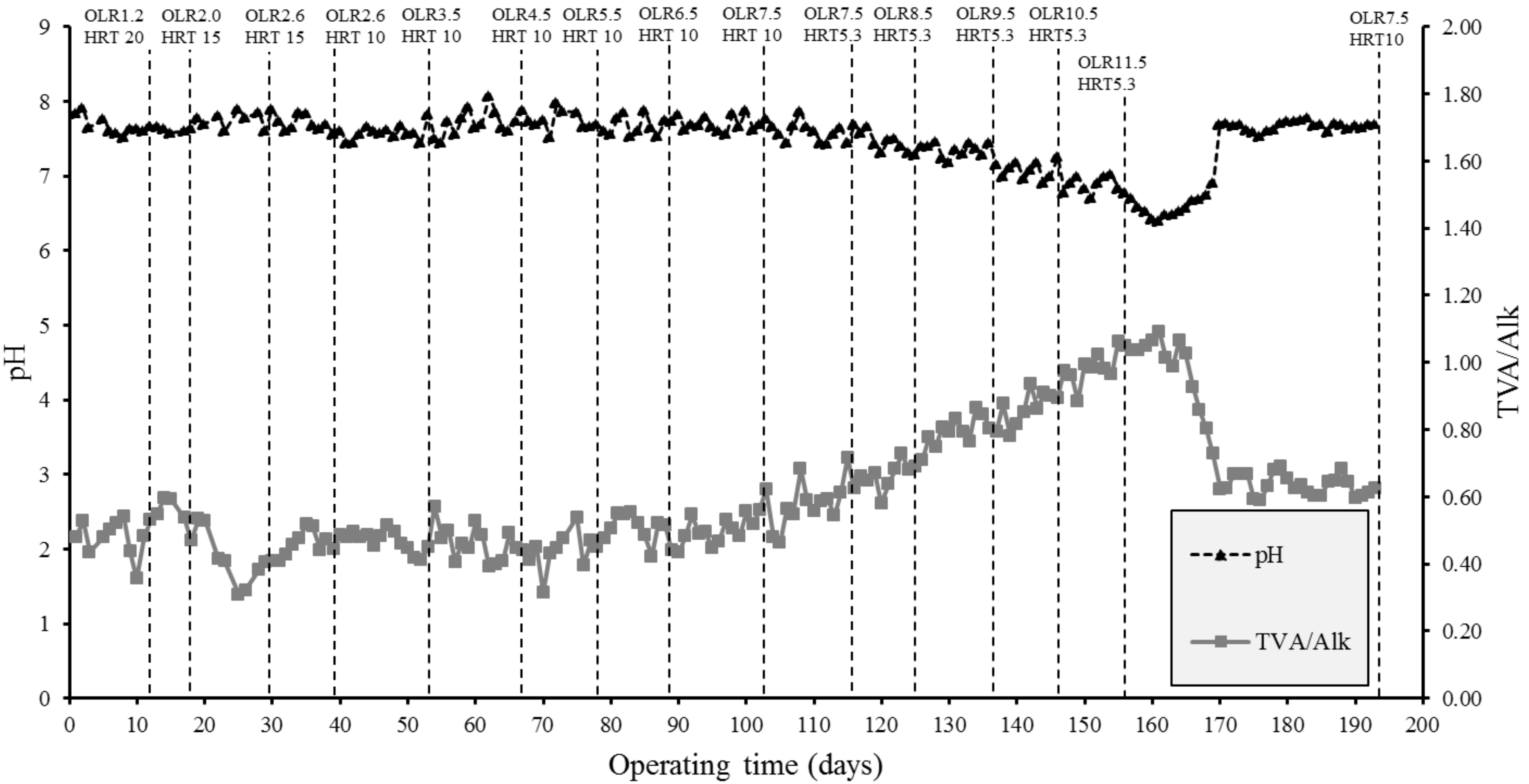

Figure 4.6 pH and ratio of TVA/Alk of thermophilic reactor under various operating conditions

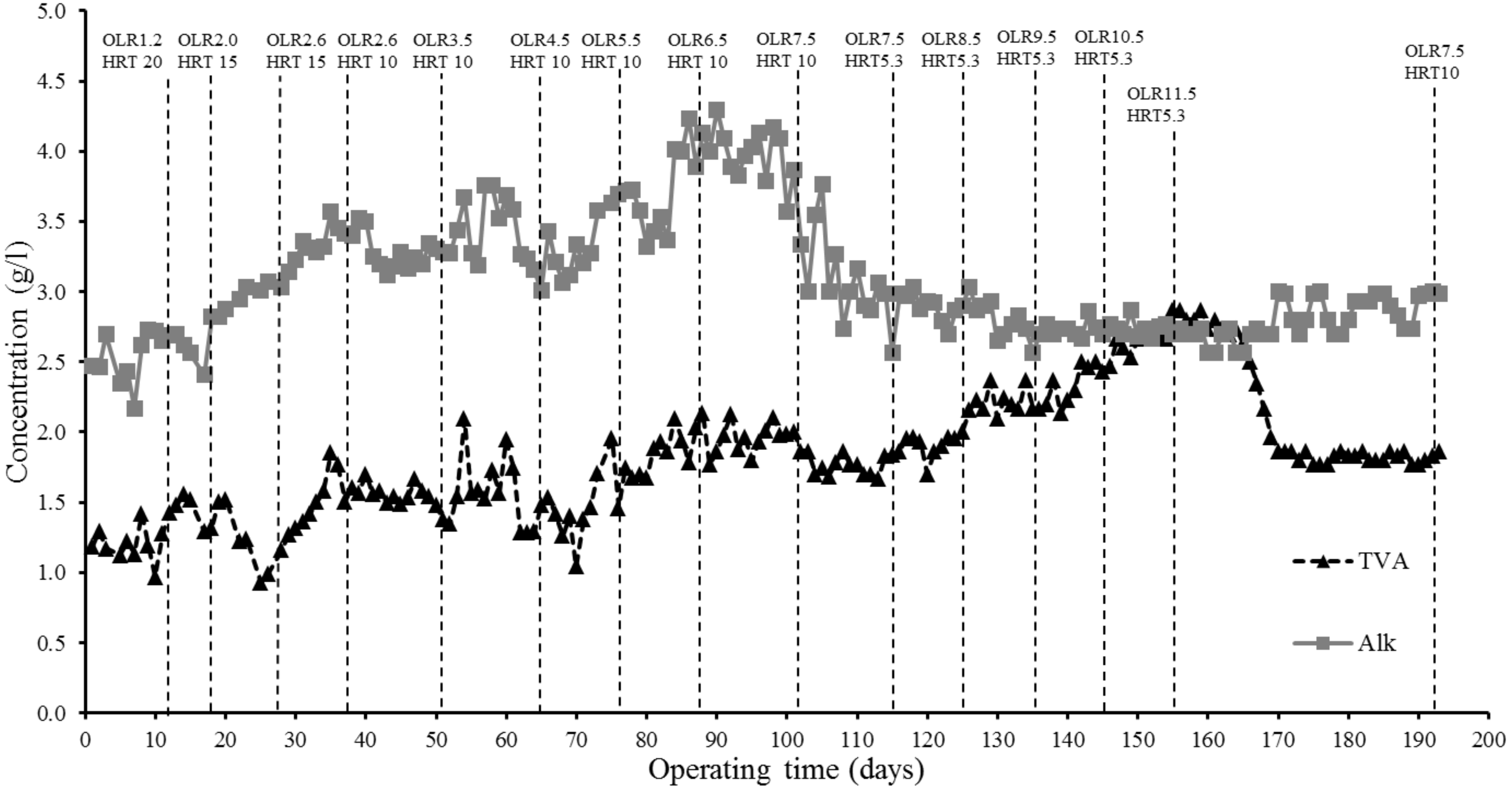

Figure 4.7 Concentration of total volatile acid (TVA) and alkalinity (Alk) from thermophilic reactor under various operating conditions

4.2.2 Reactor performance

The reactor stability was investigated for the efficiency of COD removal, methane gas production, and methane yield. The results of reactor performance at each operating condition were shown in Figure 4.8 – 4.10, and Table 4.5. The efficiency of COD removal was observed from 75 % at OLR 1.2 HRT 2.0, and high at OLR 5.5-7.5 HRT 10 with 85-90 %. COD removal at OLR 2.0 HRT 15 to OLR7.5 HRT 10 with slightly constant 85 – 90 %, at beginning, the efficiency of COD removal was fluctuated when shorten HRT from 15 d to 10 d as can notice at the condition of OLR 2.6 gCOD/l.d. The decrease of HRT will shorten contact time of POME and microbial cells that effected on microbial degradation in POME and it might be the low cell concentration at initial stage of operation. After that the operating condition was step up increased OLR at constant HRT at 10 d, the efficiency of COD removal was gradually increased until OLR 7.5 HRT 10. After that, at OLR 7.5 HRT 5.3, COD removal was decreased until OLR 11.5 HRT 5.3, COD removal was observed minimum at 61.01 %.

Methane gas production, which the value of the gas volume at standard temperature (0 ºC) and pressure (100 kPa) condition (STP), was increased with the increasing of OLR, methane gas production was highest at OLR 7.5 HRT 5.3-10 with 13-15 l/d. After OLR 8.5 HRT 5.3, methane gas production was decreased until OLR 11.5 HRT 5.3 was 7.06 l/d. The content of methane during the operating condition was found in the range of 65 – 73%. The methane yield coefficient is defined as the ratio of methane produced in this experiment to the COD utilized. The methane yield increased corresponding to the increase of the OLR and the time of AHR operation. During the initial operation of AHR, a low methane yield was obtained likely due to the organic carbon (COD) being consumed by microorganisms to build more cells during the initial startup period. Methane yield was obtained 0.40 $lCH_4/gCOD_{removed}$, which is the highest yield in this study. This value was closed to the theoretical methane yield, which is the theoretical methane yield of mesophilic anaerobic condition; there are 0.35 $lCH_4/gCOD_{removed}$.

According to the process performances of the thermophilic reactor, the reactor performance had closed the performance of the mesophilic reactor. The efficiency of COD removal at OLR 1.2 HRT 20 to OLR 7.5 HRT 10, the organic compounds concentration feed was easily biodegradable. The accumulation of organic acid production were affected to the decreasing of the reactor performance.

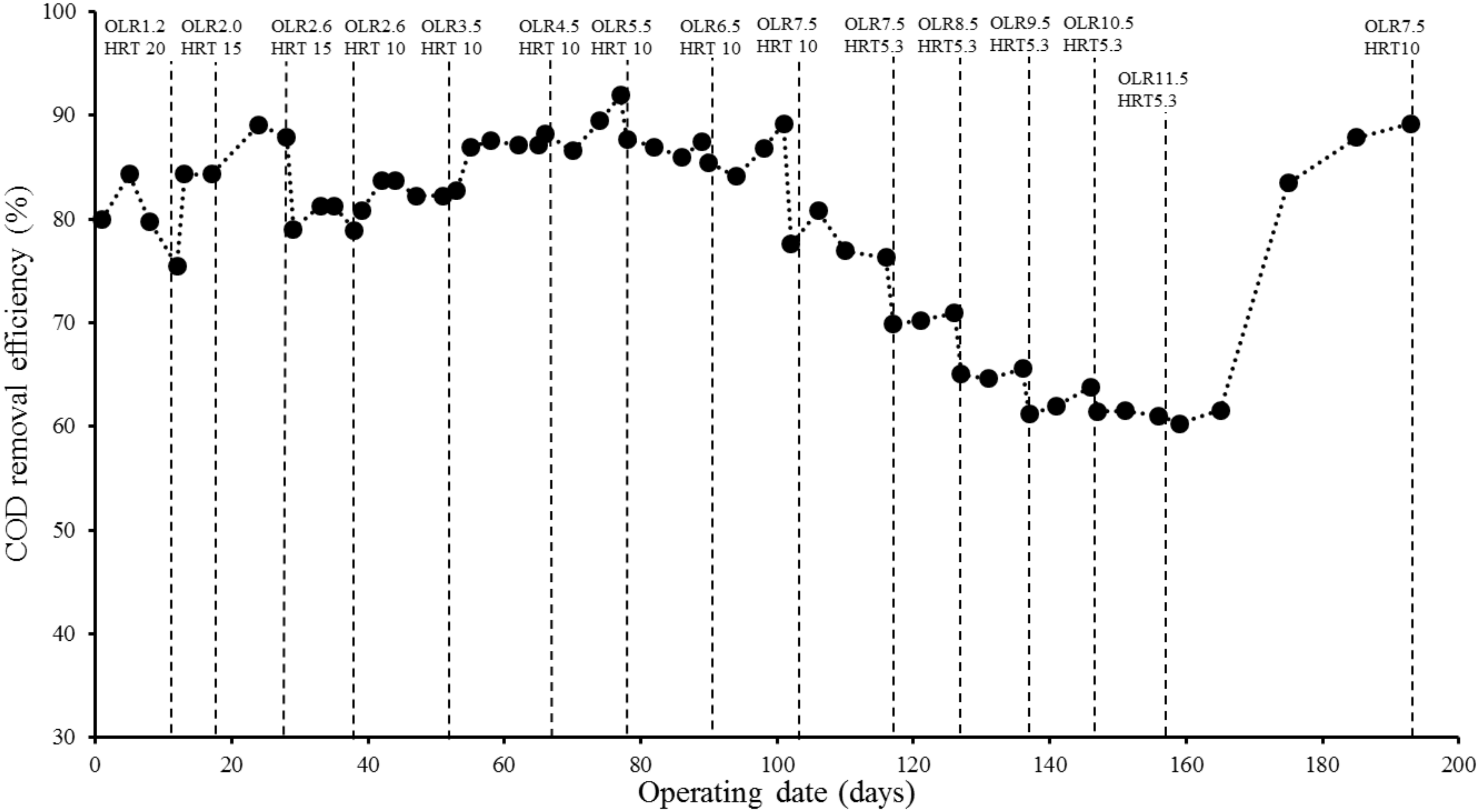

Figure 4.8 Efficiency of COD removal from thermophilic reactor under various operating conditions

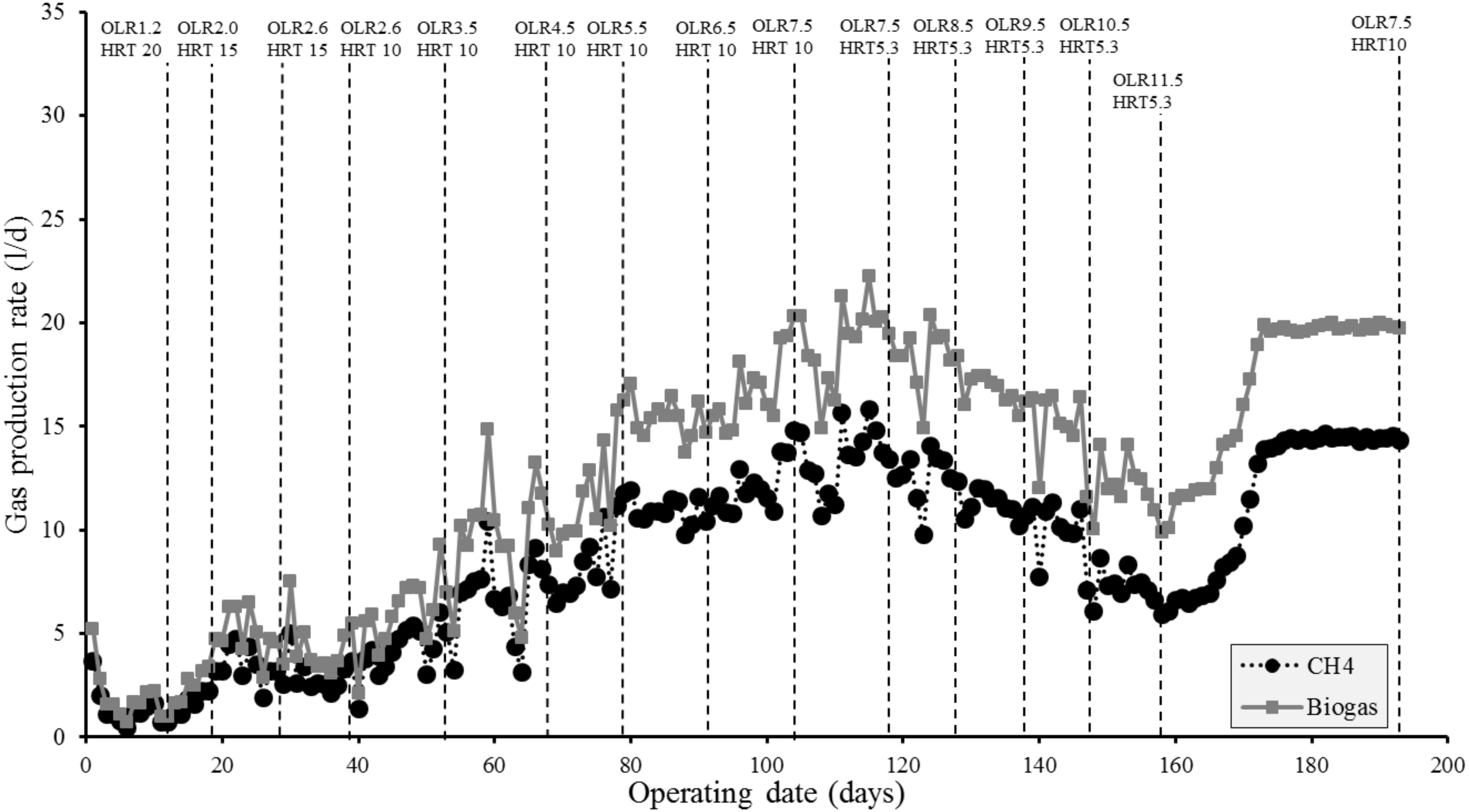

Figure 4.9 Biogas and methane production rate (STP) of thermophilic reactor under various operating conditions

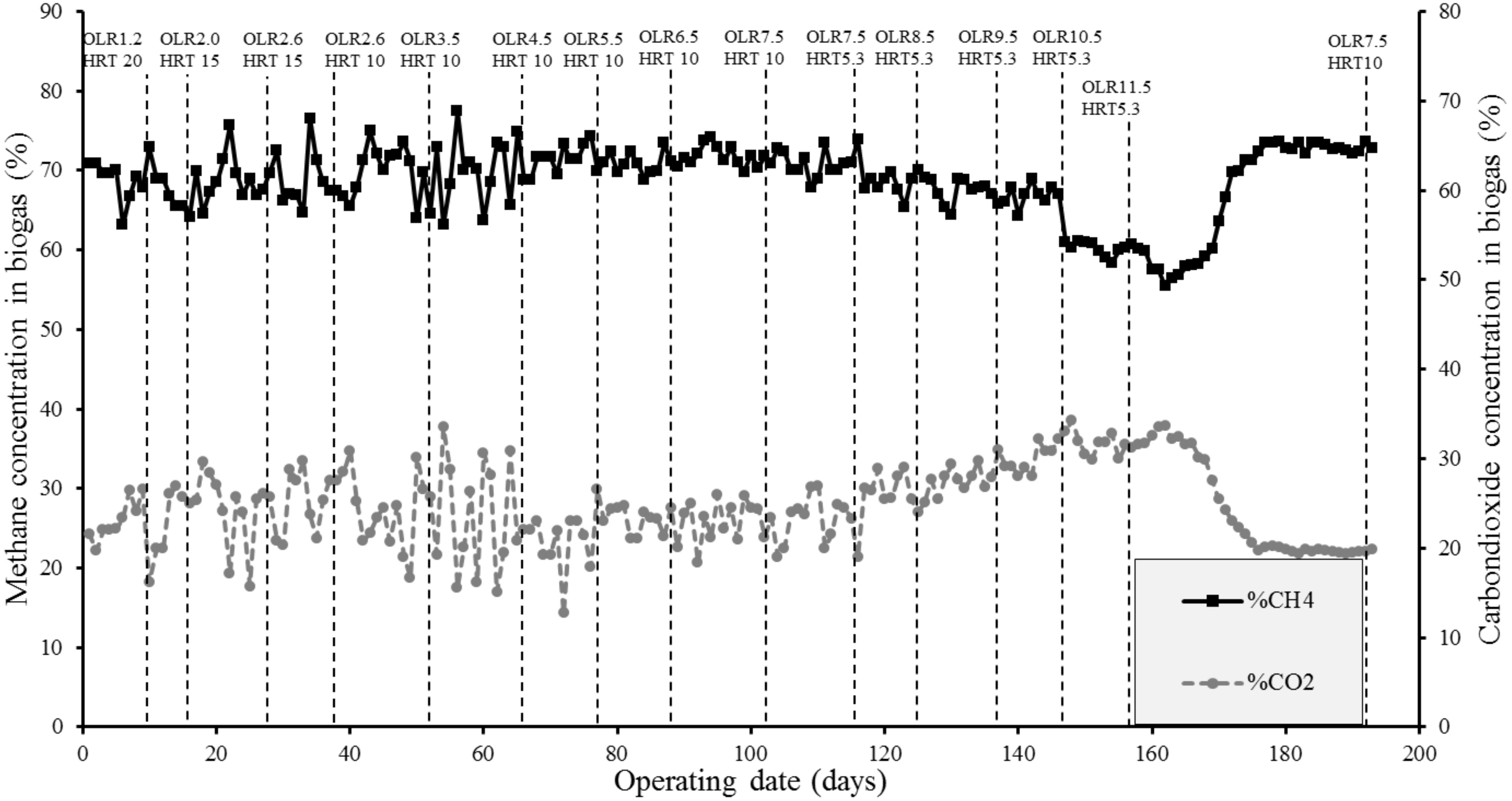

Figure 4.10 Biogas compositions in CH_4 and CO_2 of thermophilic reactor (TR) under various operating conditions

4.2.3 Microbial activity

The microbial activity of the reactor was investigated for 2 terms of specific glucose utilization (SGU) and specific methanogenic activity (SMA) for non-methanogenic, or acidogenic, and methanogenic activity, respectively. The activity of the reactor was monitored at sludge zone and packed zone of each operating conditions, there are OLR 3.5 HRT 10, OLR 5.5 HRT 10, OLR 7.5 HRT 10, OLR 7.5 HRT 5.3, and OLR 11.5 HRT 5.3. At sludge zone, the cell biomass concentration was increased from 20.1 to 120.62 gVSS/l with at the initial stage to OLR 7.5 HRT 10. After OLR 7.5 HRT 10 the cell biomass was decreased to 109.00 gVSS/l at the OLR 11.5 HRT 5.3. For SMA at sludge zone, there are started from the initial stage with 0.17 $gCOD_{methane}$/gVSS.d and maximum with 0.20 $gCOD_{methane}$/gVSS.d at OLR 7.5 HRT 10, and lowest 0.12 $gCOD_{methane}$/gVSS.d at OLR 11.5 HRT 5.3. SGU was started from 0.72 $gCOD_{glucose}$/gVSS.d and maximum 2.78 $gCOD_{glucose}$/gVSS.d at OLR 7.5 HRT 10. At packed zone, the cell biomass concentration was increased from 0.00 to 19.36 gVSS/l at the initial stage to OLR 7.5 HRT 5.3. For SMA, there are started from the initial stage with 0.00 $gCOD_{methane}$/gVSS.d and maximum with 0.24 $gCOD_{methane}$/gVSS.d at OLR 7.5 HRT 10, and lowest 0.16 $gCOD_{methane}$/gVSS.d at OLR 11.5 HRT 5.3. SGU was started from 0.00 $gCOD_{glucose}$/gVSS.d and maximum 2.52 $gCOD_{glucose}$/gVSS.d at OLR 7.5 HRT 10. The results of microbial activity of thermophilic reactor were shown in Table 4.6.

According to the microbial activity and cell biomass concentration of the thermophilic reactor, the results were similar to the microbial activity of the mesophilic reactor, more of the OLR feed into the reactor, the cell biomass concentration was increased in the packed zone and sludge zone. That effected of the feeding more organic substrate, it mean feeding more bacteria consumption substrate. The cell biomass concentration in the sludge zone was higher than packed zone, because the organic compounds were entranced into the reactor and contact with the microbial at the sludge zone as the first contact and was hydrolyzed into the organic acid and methanogens, respectively, at the sludge zone, might be most of non-methanogens. The cell biomass concentration at the packed zone might be most of methanogens. There are effected to the quality of microbial in the reactor. For SMA at the sludge zone was slightly lower than packed zone, while SGU at the sludge zone was slightly higher than packed zone. The cell biomass concentration was not significant effected to SMA, but effected to SGU. At the sludge zone, the increasing of cell biomass concentration was increased SGU. However, at the packed zone, the increasing of the cell biomass concentration was not increased SGU. It can be note that most of bacteria at the sludge zone were non-methanogens and at the packed zone was methanogens. This AHR with 50% of suspended growth and 50% of attached growth by volume can load high proportions of organic matter to 7.5 gCOD/l.d with high microbial activity and high reactor performance. The process performance and stability with organic loading fed to a high-rate anaerobic hybrid reactor for POME in this study were closed to that in the study of Meesap et al. (2012) at mesophilic temperature (30-35 °C)

The thermophilic reactor performance and stability on the POME treatment has been studied in many previous research studies. Microbial activity of acidogens and methanogens were affected to the reactor performance and stability. Khemkhao et al. (2010) was studied the upflow anaerobic sludge blanket (UASB) for POME treatment. Their results were shown that the reactor can be operated normal and good environment condition at the temperature of 57 ºC with 86 % of COD removal and methane yield 0.24 $l_{CH4}/gCOD_{removed}$ at an OLR 9.5 HRT 2.4. Compared to this study, thermophilic AHR can remove POME with 80-85% COD and methane yield 0.35-0.40 $l_{CH4}/gCOD_{removed}$ at OLR 7.5 HRT 5.3-10.

Table 4.5 Thermophilic reactor performance for POME treatment in other research studies

Reactor	Waster	OLR (gCOD/l.d)	HRT (days)	COD removal (%)	Methane yield ($l_{CH4}/gCOD_{removed}$)	Reference
UASB (57ºC)	POME	9.5	2.4	86	0.24[a]	Khemkhao et al., [13]
AHR (55 ºC)	POME[b]	1.5	6.2	87	0.13	Joo-Young Jeong et al., [38]
AHR (55ºC)	POME	7.5	5.3-10	80-85	0.35-0.40	This research

Note: [a]Calculated from the research information

[b]POME was pre-treat by screw decanter, to reduce SS and oil

Table 4.6 Microbial activity of thermophilic reactor

Condition	Cell biomass concentration		Activity			
	Sludge zone (gVSS/l)	Packed zone (gVSS/l)	SMA ($gCOD_{methane}/gVSS.d$)		SGU ($gCOD_{glucose}/gVSS.d$)	
			Sludge zone	Packed zone	Sludge zone	Packed zone
Initial	20.10	0.00	0.17	0.00	0.72	0.00
OLR 3.5 HRT 10	39.05	12.16	0.14	0.19	2.48	2.33
OLR 5.5 HRT 10	60.87	12.27	0.12	0.18	2.32	2.41
OLR 7.5 HRT 10	120.62	18.66	0.20	0.24	2.78	2.52
OLR 7.5 HRT 5.3	110.13	19.36	0.21	0.21	2.53	2.01
OLR 11.5 HRT 5.3	109.00	17.87	0.12	0.16	2.47	1.98

Table 4.7 Process performance and stability of thermophilic reactor under each operating condition

Condition	OLR (gCOD/l.d)	HRT (Days)	Stability				Performance		
			pH	Alk (mg/l)	TVA (mg/l)	TVA/Alk	COD removal (%)	CH_4 (l/d)	Methane yield ($lCH_4/gCOD_{removal}$)
1	1.2	20	7.73	2,540	1,220	0.48	75.48	0.69	0.34
2	2.0	15	7.79	2,570	1,460	0.57	84.30	2.72	0.21
3	2.6	15	7.76	2,950	1,240	0.42	87.84	3.18	0.24
4	2.6	10	7.72	3,350	1,520	0.45	78.89	3.29	0.20
5	3.5	10	7.58	3,290	1,535	0.47	82.78	5.08	0.31
6	4.5	10	7.71	3,425	1,590	0.46	87.11	8.29	0.37

4.3 Effect of mesophilic and thermophilic temperature on reactor performance, stability and microbial activity

4.3.1 Reactors stability

The process stability of the reactors controlling at mesophilic (35ºC) and thermophilic (55ºC) temperatures was investigated. At the condition of OLR 1.2 gCOD/l.d HRT 20 days to OLR 7.5 gCOD/l.d HRT 10 days, the stability of mesophilic reactor (MR) and thermophilic reactor (TR) was achieved in normal condition by pH constant with 7.0 – 8.0 (Figure 4.11). Along the operation, the concentrations of TVA and Alk were in the range of 1,000-1,800 mg/l and 2,000-4,000 mg/l, respectively. However, at the operating condition OLR 1.2 – 7.5 gCOD/l.d, TVA/Alk ratio was lower than 0.5. Both reactors were achieved the reactors stability in similar trend. After the condition of OLR 7.5 gCOD/l.d HRT 10 days, the reactors (MR and TR) stabilities were found low stability. It was signal of failure conditions as illustrated in Figure 4.12. Under these operations, pH and TVA/Alk ratio were high acidic and lower buffer capacity. TR at the condition of OLR 11.5 gCOD/l.d HRT 5.3 days, the lowest pH and TVA/Alk ratio were 6.88 and 1.10, respectively. MR at the condition of OLR 11.5 gCOD/l.d HRT 5.3 days, the lowest pH and TVA/Alk ratio were 6.58 and 1.06 respectively.

Under these condition, the reactors stability were affect to the reactors performance as demonstrated in the previous subject matter. Under these conditions were resulted in high organic acid substrate, which high concentration substrate, which could not be suitable for reactors metabolize. At the all of the reactors operation conditions, TVA of TR was slightly higher than MR. There are at the higher temperature condition, the volatile fatty acid was produced and consumed more mesophilic temperature range [11]. After the condition of OLR 7.5 gCOD/l.d HRT 5.3 days, TR showed the results of pH, TVA/Alk ratio better than MR, that effected to the reactors performance, which at high substrate concentration, TR can be achieved the performances higher than MR. These results were according with at thermophilic temperature range; the substrate degradation rate was higher than mesophilic temperature range, that able to operate with higher OLRs and shorter HRT while can produce more biogas [10]. After the condition of OLR 11.5 HRT 5.3, the reactors were stopped feeding 5 days and were operated at the condition of OLR 7.5 HRT 10, MR was used 21 days to adjust to normal condition, while TR was used 14 days. Therefore, the TR was the reactor flexibility slightly higher than MR.

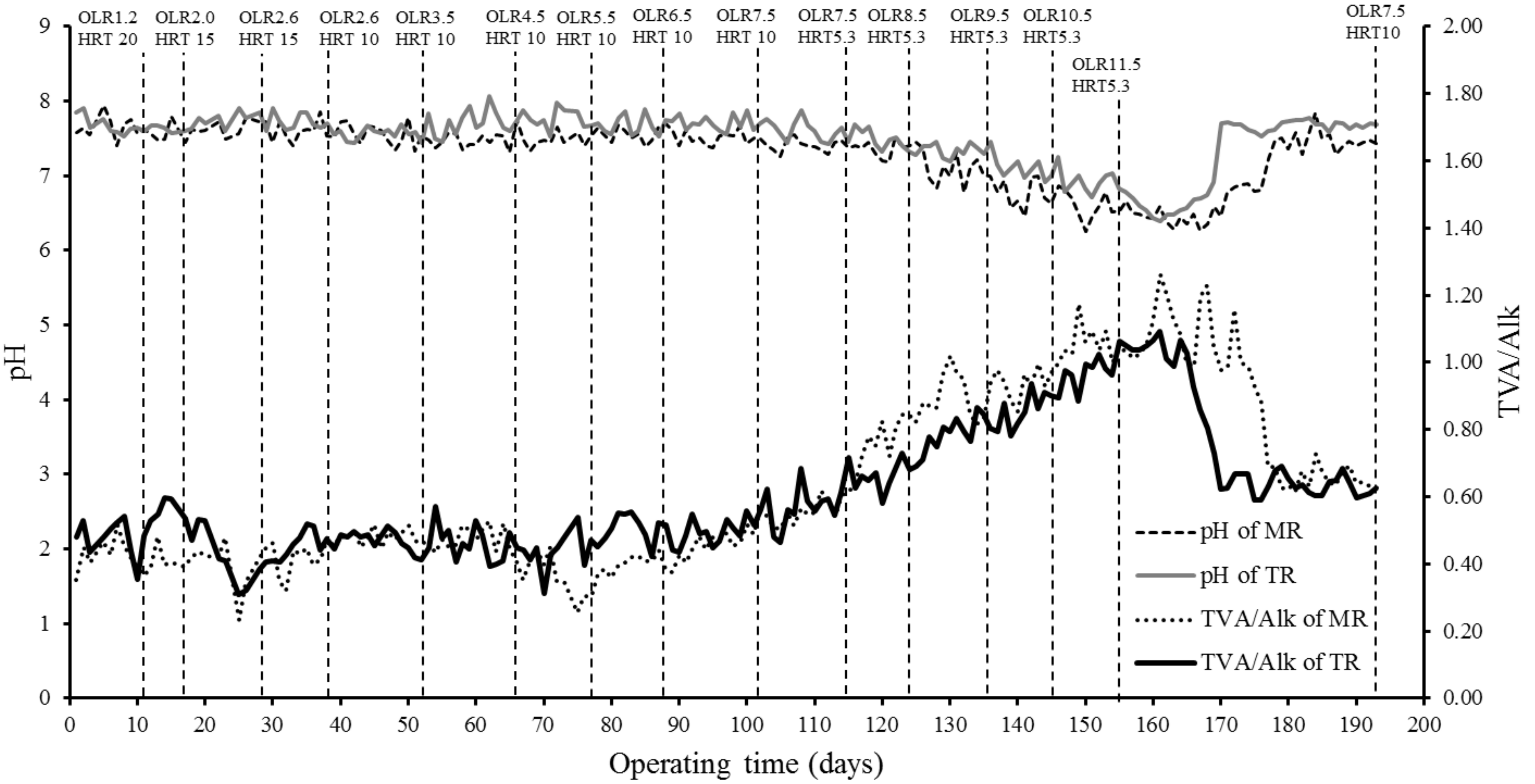

Figure 4.11 pH and TVA/Alk ratio of mesophilic (MR) and thermophilic (TR) reactors under various operating conditions

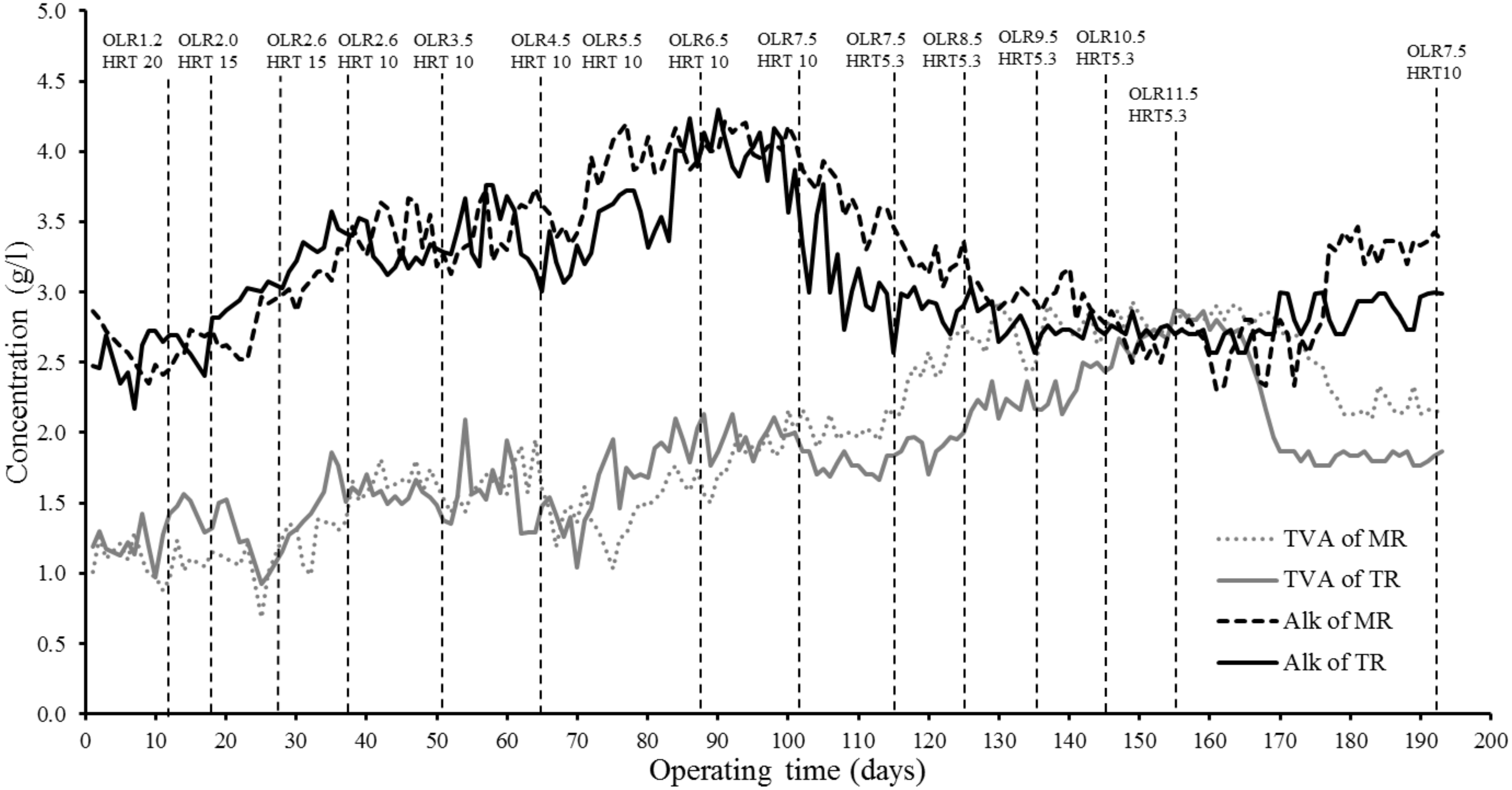

Figure 4.12 Total Volatile Acid (TVA) and Alkalinity (Alk) of mesophilic (MR) and thermophilic (TR) reactors under various operating conditions

4.3.2 Reactor performance

A successful operation of the AHRs at MR and TR were achieved in 193 days, with maximum condition OLR 11.5 gCOD/l.d and 5.3 days of HRT. Effect of operating condition on reactors performance was shown in Figures 4.12- 4.16 and Table 4.8. Figure 4.13 was shown the percentage of COD removal from anaerobic digestion of POME in the AHRs at each operating condition. Not much significant difference in trend COD removal of two reactors among fifteen operating conditions. The efficiency of COD removed was achieved highest in the range of 80 – 90% for OLR 1.2 dCOD/l.d and HRT 20 days to OLR 7.5 gCOD/l.d and HRT 10 days. After that the efficiency of COD removal was gradually decreased until OLR 11.5 gCOD/l.d HRT 5.3 days, the efficiency of COD removal was lower than 60%. It can be noted that the reactor temperature was not significant effected to the performance of COD removal. The concentration of methane was achieved highest in the range of 60-70%. After that the concentration of methane was decreased until lower than 60% at the condition of OLR 11.5 gCOD/l.d HRT 5.3 days, while the concentration of carbon dioxide was increased. It can be noted that the increasing of COD concentration influent that effected to the reactors performance in term of the quality of biogas production. Figure 4.15 was show the performance of the AHRs in methane gas production at different operating condition. Not much significant difference between the trend of methane gas production of mesophilic reactor and thermophilic reactor, it was found that the methane gas production was closely correlated with the increasing of OLR. The increasing of OLR from 1.2 to 7.5 gCOD/l.d, the methane gas production was increased from 0.69 to 14.81 l/d and 1.31 to 12.75 l/d of thermophilic and mesophilic reactors, respectively. After OLR 7.5 gCOD/l.d HRT 5.3 days, the methane gas production was decreased until OLR 11.5 gCOD/l.d HRT 5.3 days, the methane gas production was 7.06 and 5.38 l/d of thermophilic and mesophilic reacots respectively.

These effects were similarly the phenomena of the increasing and decreasing of COD removal. The methane yield coefficient is defined as the ratio of methane produced in this experiment to the COD utilized. The methane yield of the both reactors was increased corresponding to the increasing of the OLR and the time of AHRs operation as shown in Table 4.8 and Figure 4.16. Methane yield obtained at 0.40 and 0.35 $lCH_4/gCOD_{remove}d$ of thermophilic and mesophilic reactors respectively, which is the highest yield in this study. The efficiency of COD removed and methane yield were close to the theoretical methane yield of 0.35 $lCH_4/gCOD_{removed}$ [39].

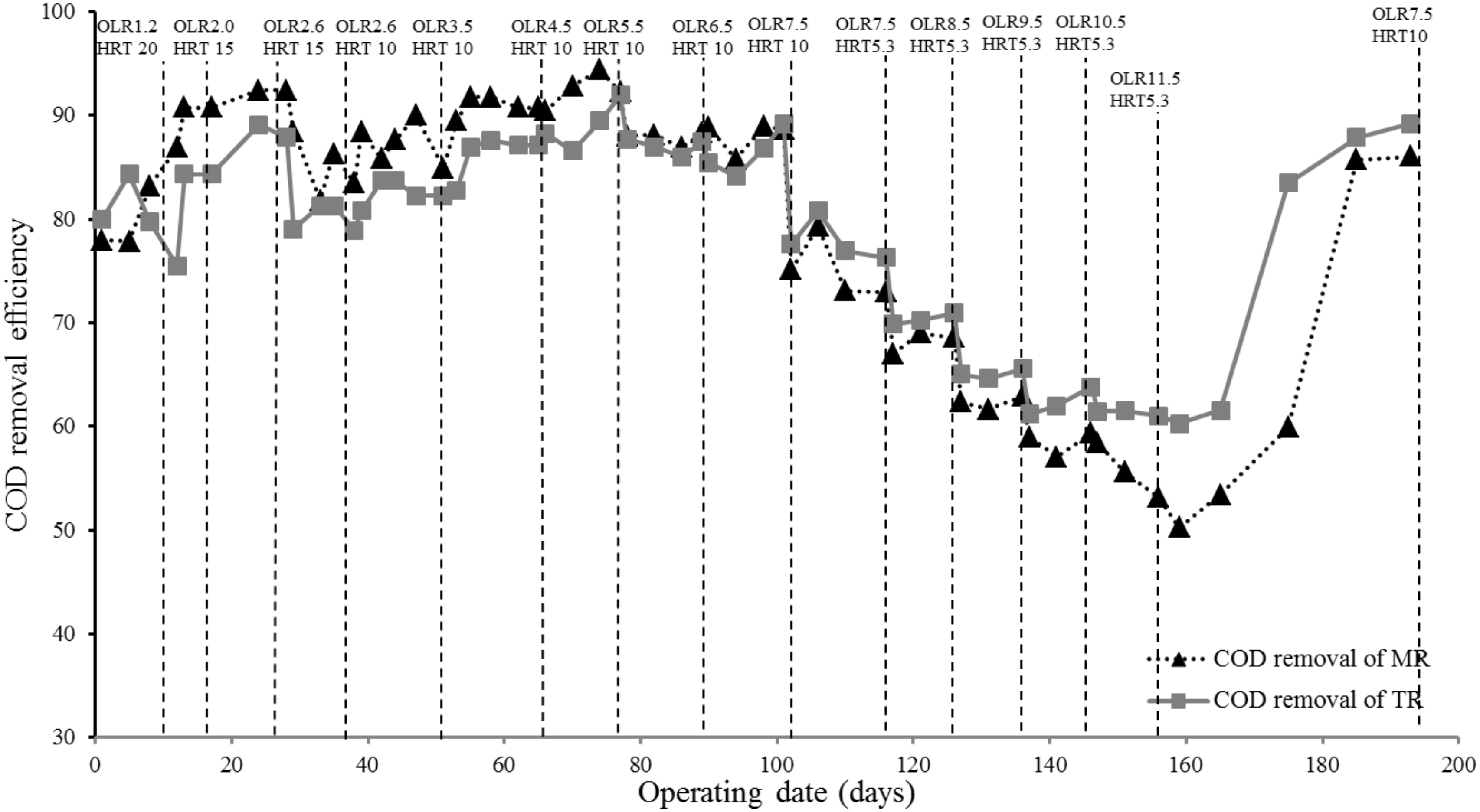

Figure 4.13 Efficiency of COD removal from mesophilic (MR) and thermophilic (TR) reactors under various operating conditions

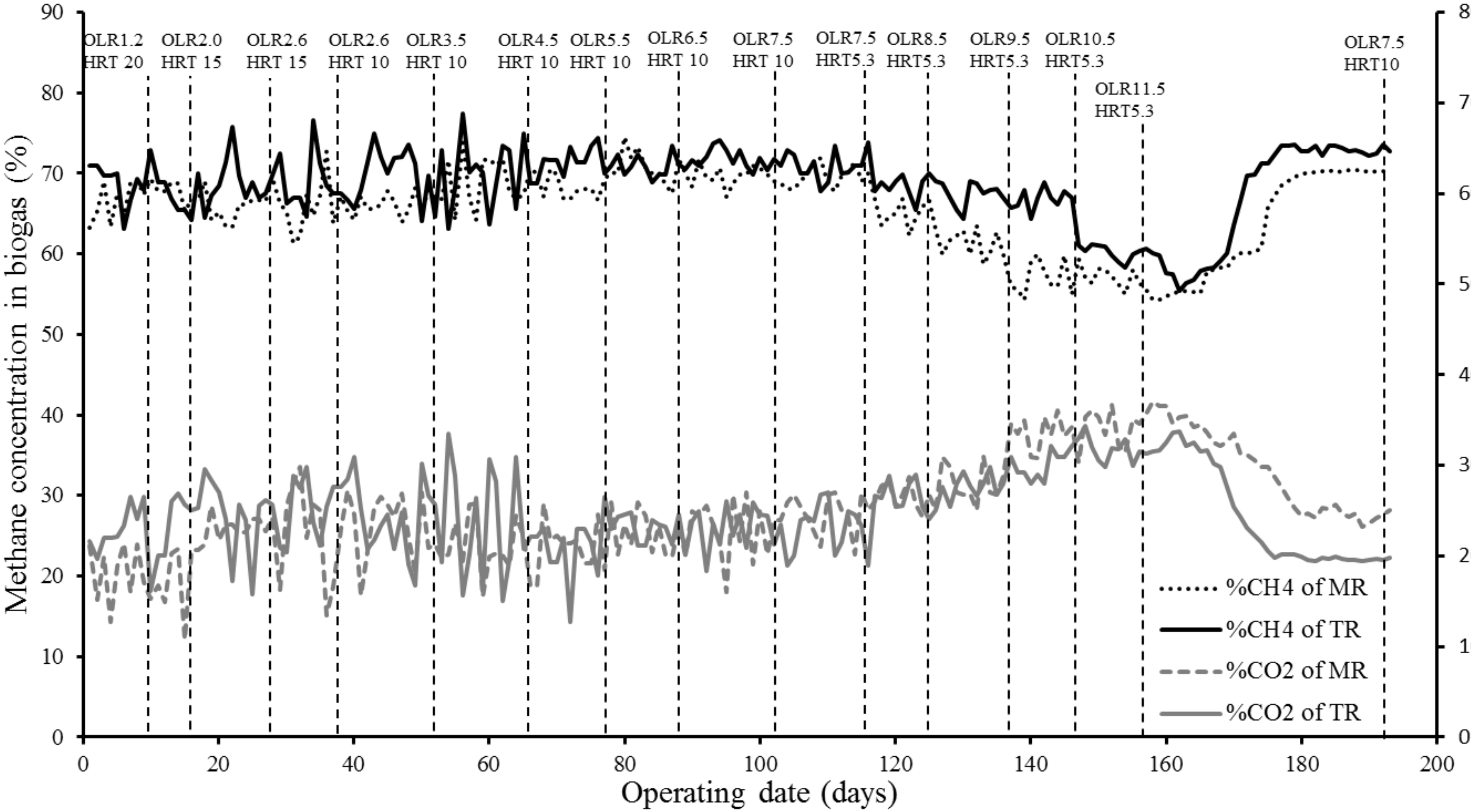

Figure 4.14 Concentration of CH_4 and CO_2 from mesophilic (MR) and thermophilic (TR) reactors under various operating conditions

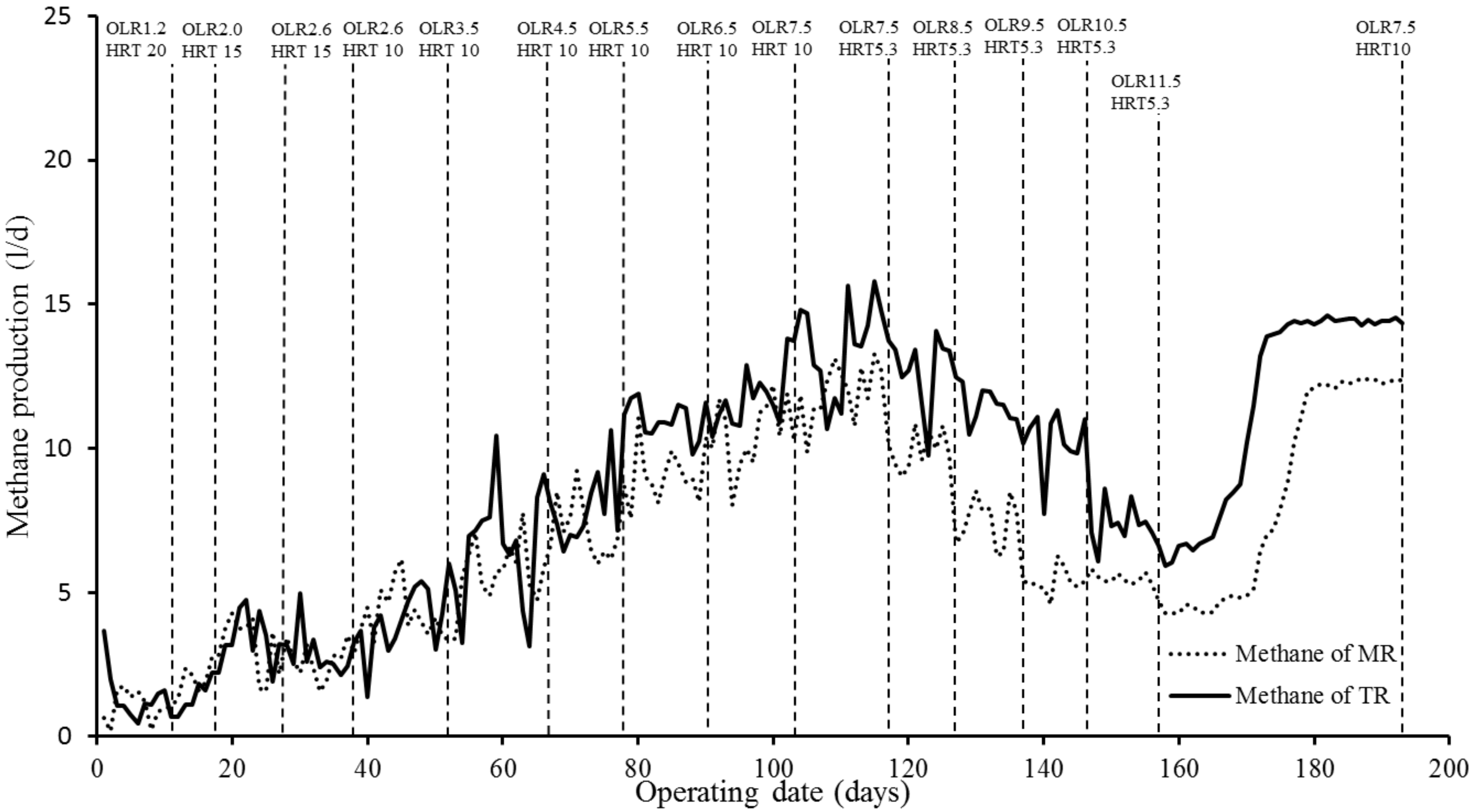

Figure 4.15 Methane production of mesophilic (MR) and thermophilic (TR) reactors under various operating conditions

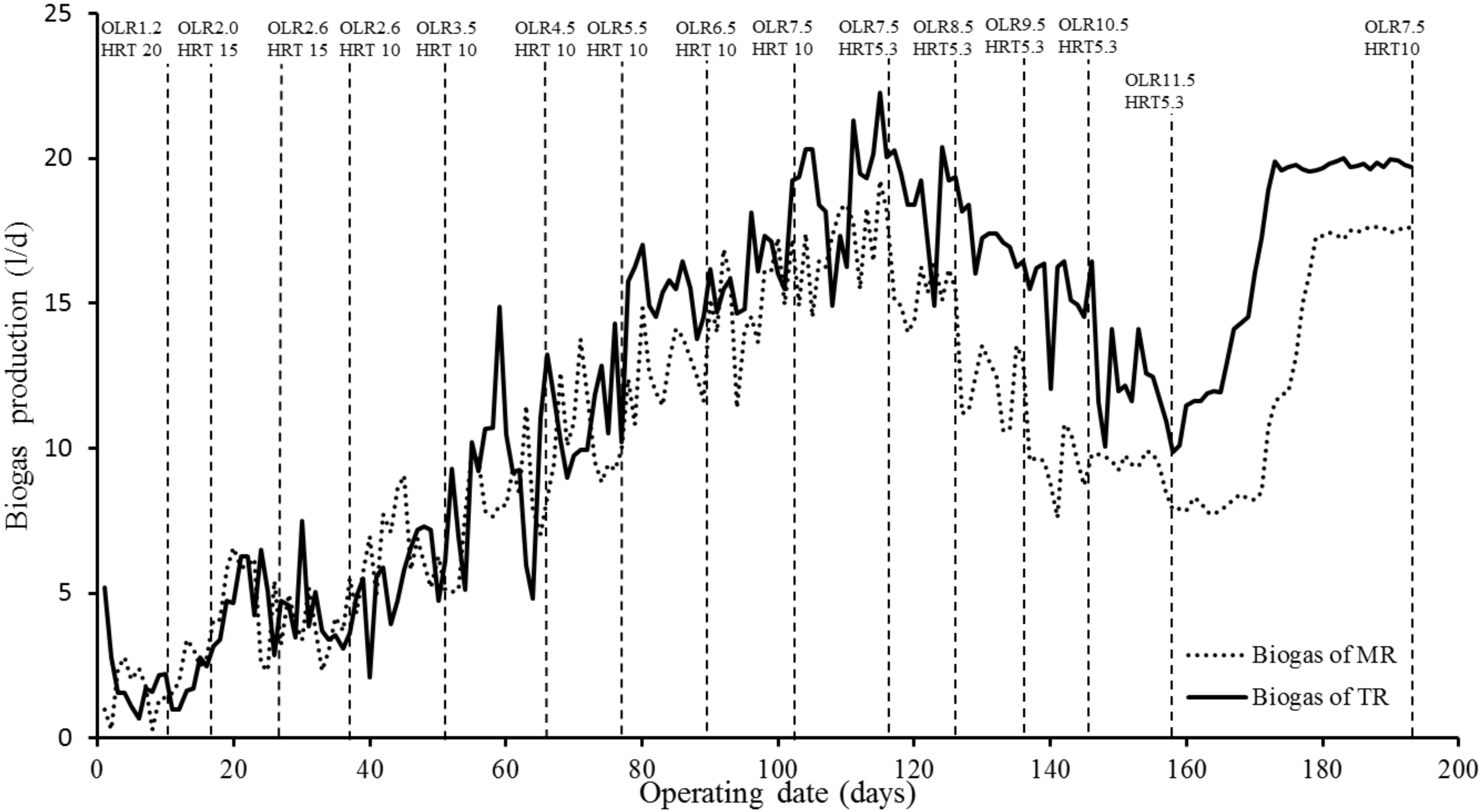

Figure 4.16 Biogas production of mesophilic (MR) and thermophilic (TR) reactors under various operating conditions

Table 4.8 COD removal efficiency and Methane yield at the end of each operating condition

Condition	OLR (gCOD/l.d)	HRT (Days)	COD removal (%)		Methane yield ($lCH_4/gCOD_{removal}$)	
			MR	TR	MR	TR
1	1.2	20	86.89	75.48	0.16	0.20
2	2.0	15	90.75	84.30	0.17	0.17
3	2.6	15	92.39	87.84	0.30	0.24
4	2.6	10	83.48	78.89	0.24	0.20
5	3.5	10	89.48	82.78	0.24	0.25
6	4.5	10	90.75	87.11	0.29	0.29

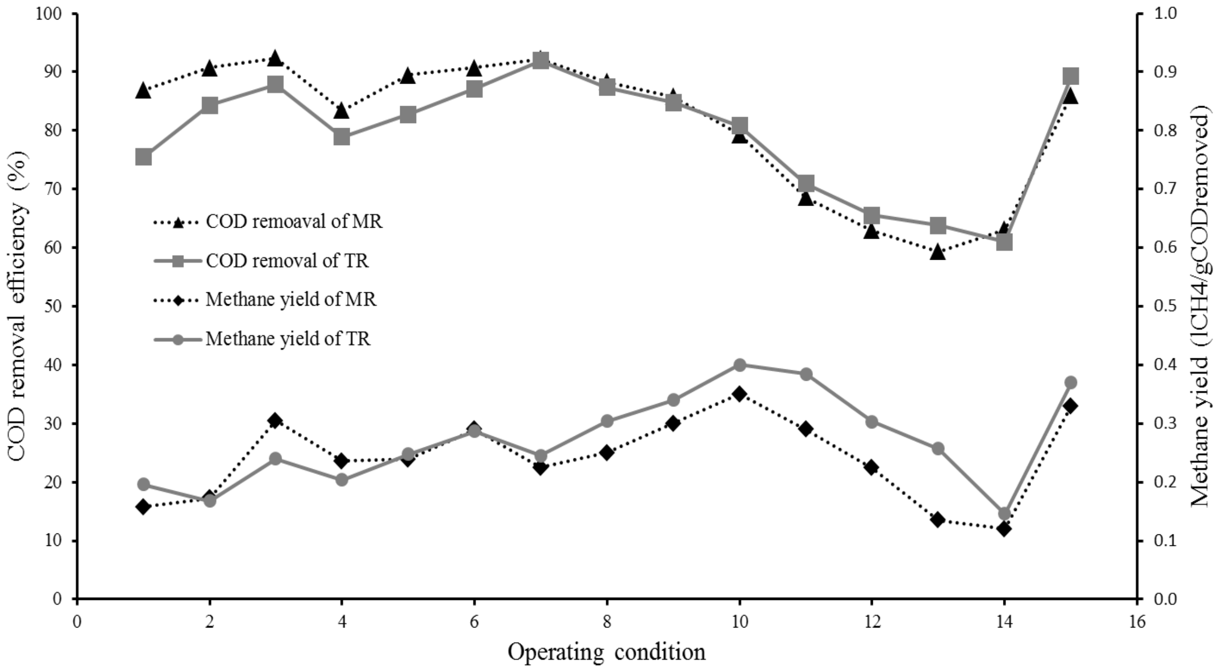

Figure 4.17 COD removal efficiency and Methane yields of MR and TR at the end of each operating condition

4.3.3 Acidogenic and methanogenic activities

The seed was collected from Chonburi Province, which operated in a mesophilic cover lagoon anaerobic system. For mesophilic reactor, the seed was applied into the reactor immediately. For thermophilic reactor, the seed was acclimatized to 55 °C by step increased temperature 5 ºC/day before applied into the reactor. Then applied these inoculum seeds in concentration of 20 gVSS/l to 6 l of AHR. The cell biomass in sludge and packed zones were monitored at operating condition OLR 3.5 HRT 10, OLR 5.5 HRT 10, OLR 7.5 HRT 10, OLR 7.5 HRT 5.3, and OLR 11.5 HRT 5.3 (Figure 4.18 – 4.19). The cell biomass of mesophilic and thermophilic reactors were similar trend. The cell biomass concentration was more increased in sludge zone while that in packed was slightly constant when increased OLR 3.5 gCOD/l.d HRT 20 days to 7.5 gVSS/l.d HRT 5.3 days. After the condition of OLR 7.5 gCOD/l.d HRT 5.3 days, the cell biomass concrentration was founding slightly decreased, which related to the reactors performance and stability. It can be note that the concentration of cell biomass in the reactors was the one of factor to control the reactors performance and stability. At the all of operating condition, for the cell biomass concentration of thermophilic reactor at sludge zone was more than the cell biomass concentration of mesophilic reactor, while at packed zone the cell biomass concentration of thermophilic reactor was lower than the cell biomass concentration of mesophilic reactor. It can be noted that, the quantity of bacteria population in sludge zone, which may be maintain with most of acidogens, was growth well with thermophilic temperature, while the quantity of bacteria population in packed zone, which may be maintain with most of methanogens, was growth well with mesophilic temperature, as show in Figure 4.18. However, total cell biomass was increased from 20.10 (initial seed) to maximum 139.28 and 130.94 gVSS/l.d at OLR 7.5 gCOD/l.d HRT 10 days for thermophilic and mesophilic reactors respectively, as shown in Figure 4.18. The cell biomass related to amount of substrate as food and increased the reactor performance in POME treatment and methane production.

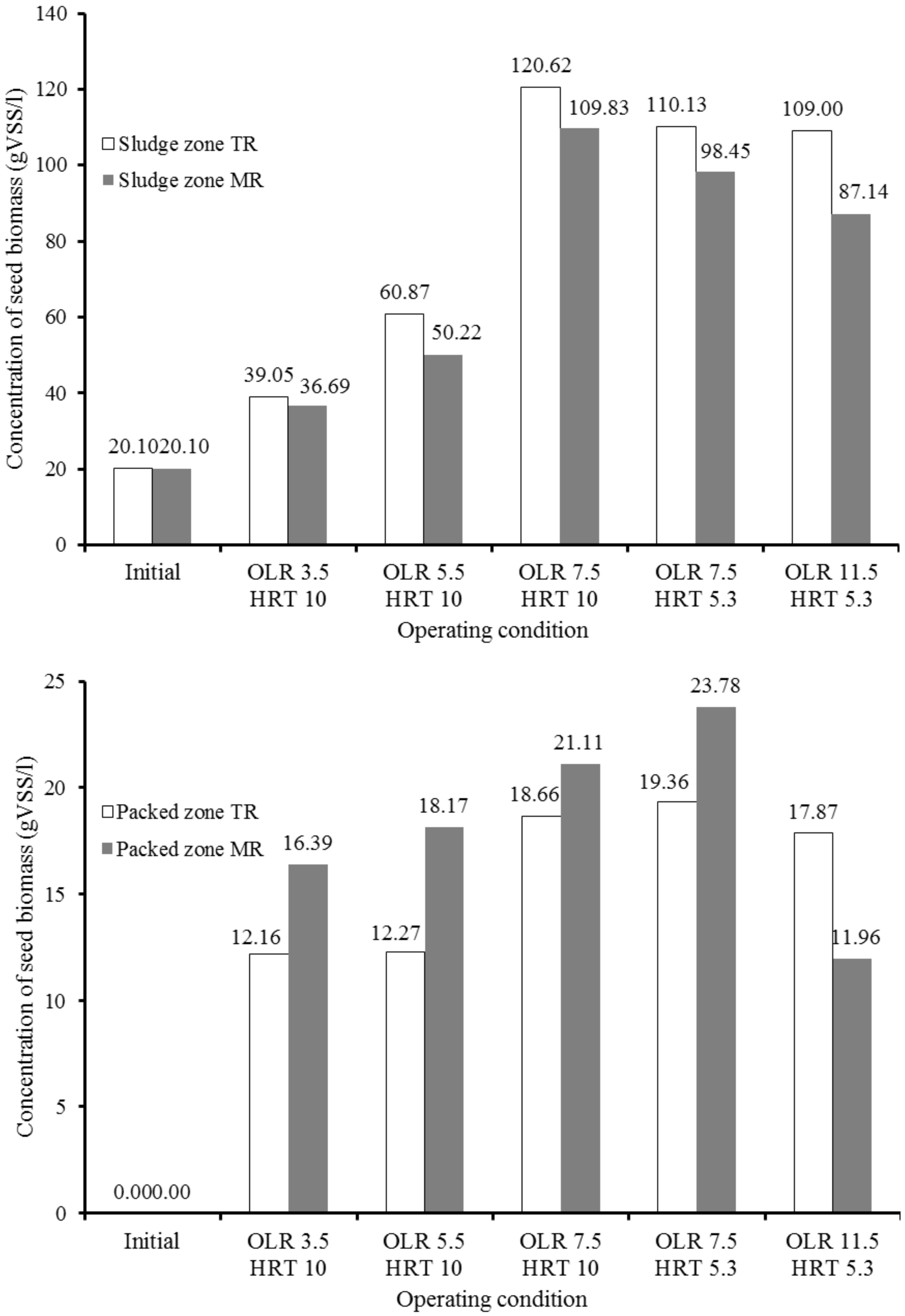

Figure 4.18 Cell biomass concentrations in (a) sludge zone and (b) packed zones of TR and MR under each operating condition

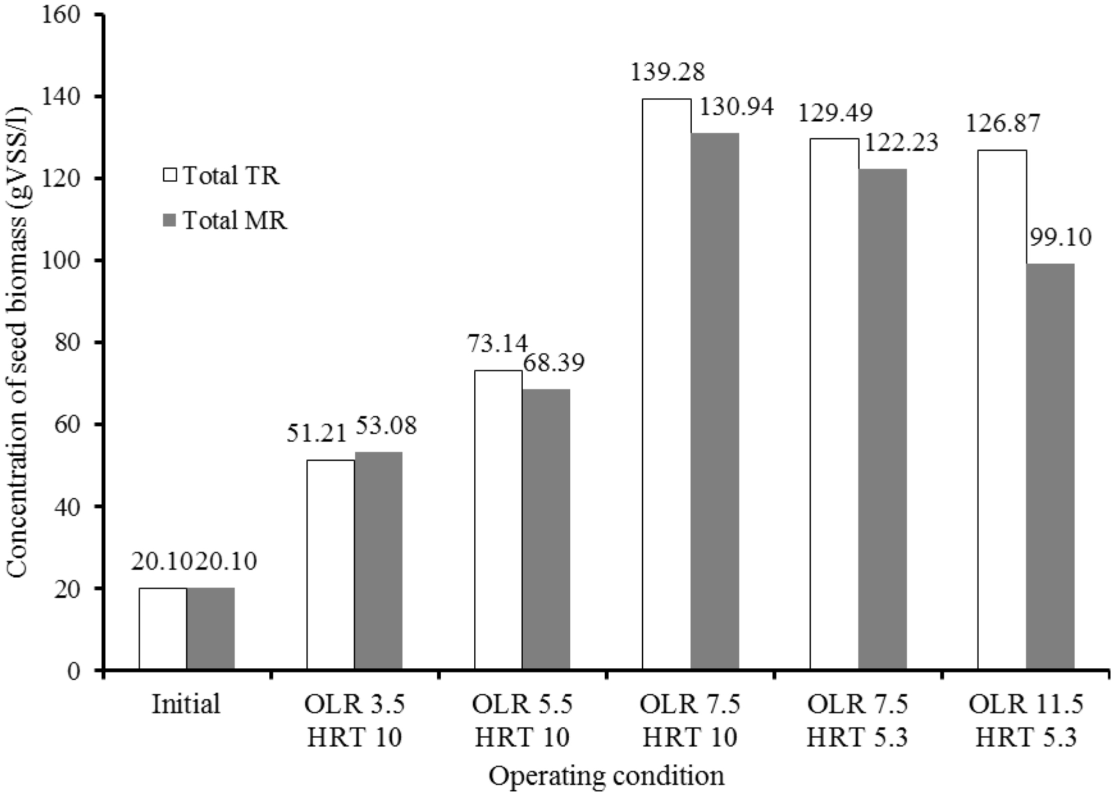

Figure 4.19 Total cell biomass concentrations of TR and MR under each operating condition

Not only the quantity of microbial cells will affect reactor performance but the microbial quality in terms of microbial activity was also important. Microbial activities for acidogens and methanogens at operating condition initial OLR 3.5 HRT 10, OLR 5.5 HRT 10, OLR 7.5 HRT 10, OLR 7.5 HRT 5.3, and OLR 11.5 HRT 5.3 of mesophilic and thermophilic reactors were shown in Tables 4.9 – 4.10. Comparison acidogenic and methanogenic activities of thermophilic (TR) and mesophilic (MR) reactors, non-methanogens activity (acidogenic activity) was increased related with the increasing of OLR until the condition of OLR 7.5 HRT 10, SGU of thermophilic reactor was higher than mesophilic reactor at the both of sludge zone and packed zone. SMA was increased followed the increasing of OLR until OLR 7.5 HRT 10. At the sludge zone, SMA of thermophilic reactor was slightly higher than mesophilic reactor, while at the packed zone the SMA of mesophilic reactor was higher than thermophilic reactor. At operating condition of OLR 3.5 HRT 10, acidogenic activity increased and methanogens activity of two reactors slightly decreased compared to that in the startup seed. When the organic pollutant concentration was increased from the OLR 3.5 to the OLR 7.5 HRT 10 conditions, the activities of the acidogens and methanogens in the two reactors at the sludge and packed zones were investigated for the development of these characteristics. In the sludge zone, the acidogenic activity was not significantly increased from 2.48 to 2.78 and 1.05 to 2.59 $gCOD_{glucose}$/g VSS.d of thermophilic and mesophilic reactors at OLR 7.5 HRT 10, respectively, while the methanogenic activity was slightly increased from 0.14 to 0.20 and 0.11 to 0.19 $gCOD_{CH4}$/gVSS.d of thermophilic and mesophilic reactors at OLR 7.5 HRT 10, respectively. In the packed zone, the acidogenic activity had not significantly increased from 2.33 to 2.52 and 1.35 to 2.23 $gCOD_{glucose}$/g VSS.d of thermophilic and mesophiliec reactors at OLR 7.5 HRT 10, respectively, while the methanogenic activity was slightly constant at around 0.16 – 0.24 and 0.16 – 0.25 $gCOD_{CH4}$/gVSS.d of thermophilic and mesophiliec reactors at OLR 7.5 HRT 10, respectively. After the condition of OLR 7.5 HRT 10, the activities were slightly decreased until OLR 11.5 HRT 5.3. In packed zone the non-methanogen activity was 1.98 and 1.94 $gCOD_{glucose}$/g VSS.d of thermophilic and mesophiliec reactors, respectively. At the increasing of OLR was effected to the proceeding of microbial activities, to high substrate was occurred high TVA production and accumulation, which due to the condition not optimized to methane production, and it was unsuccessfully utilized by methanogens in the reactors.

The action of the sludge and packed zones, which work as hydrolysis fermentative and methanogenesis zones were mostly responsible for a properly enhanced reactor performance and maintained the process stability of the AHRs. For POME, anaerobic digestion could be achieved completely within one reactor of an anaerobic hybrid reactor.

Table 4.9 Microbial activities of SGU in sludge and packed zones of TR and MR

Condition	Sludge zone ($gCOD_{glucose}$/gVSS.d)		Packed zone ($gCOD_{glucose}$/gVSS.d)	
	TR	MR	TR	MR
Initial	0.72	0.77	0.00	0.00
OLR 3.5 HRT 10	2.48	1.05	2.33	1.35
OLR 5.5 HRT 10	2.32	2.32	2.41	2.01
OLR 7.5 HRT 10	2.78	2.59	2.52	2.23
OLR 7.5 HRT 5.3	2.53	2.08	2.01	2.16
OLR 11.5 HRT 5.3	2.47	1.83	1.98	1.94

Table 4.10 Microbial activities of SMA in sludge and packed zones of TR and MR

Condition	Sludge zone ($gCOD_{methane}/gVSS.d$)		Packed zone ($gCOD_{methane}/gVSS.d$)	
	TR	MR	TR	MR
Initial	0.17	0.26	0.00	0.00
OLR 3.5 HRT 10	0.14	0.11	0.19	0.16
OLR 5.5 HRT 10	0.12	0.11	0.18	0.23
OLR 7.5 HRT 10	0.20	0.19	0.24	0.25
OLR 7.5 HRT 5.3	0.21	0.14	0.21	0.23
OLR 11.5 HRT 5.3	0.12	0.09	0.16	0.16

The results of the reactor performance, stability and microbial activity were related with the seed characteristics. The initial seed sludge was collected from anaerobic system, which operated with 35 °C condition, and was acclimatized to 55 °C for thermophilic reactor.

Hydrolytic, acidogenics, and acetogenic bacteria or non-methanogens were often the anaerobic digestion process stability. Therefore, in this research the thermophilic reactor was stable closely to the mesophilic reactor at the high OLRs conditions. For methanogens, which are acetotrophic and hydrogenotrophic methanogens, acetotrophic methanogen was hardly changed with the transition of reactor temperature, but hydrogenotrophic methanogen was changed with the transition of the reactor temperature. At thermophilic condition, some of methanoseta species were existed. However, most of bacteria in the reactor were originated from raw POME; some of them were originated from the seed sludge [10], [11], and [13]. These results were supported with the microbial activity results of the both reactors. The specific glucose utilization (SGU) of the thermophilic reactor was higher than mesophilic reactor at the sludge zone and packed zone with all of operating conditions, while the specific methanogenic activity (SMA) of thermophilic and mesophilic reactor was not significant difference at the all of operating conditions. That effected to the performance of the both reactors not significant difference.

4.4 System analysis

System analysis was used for analyzing the performance of AHR for POME treatment, including biogas and electricity production systems. The system was focused on the scope of financial analysis (investment cost and profit), environmental analysis (value of GHG, carbon dioxide and methane, emission) and energy analysis (energy value of biogas production). Three terms of the system analysis were used to selection the difference of the POME treatment systems, which are thermophilic and mesophilic anaerobic reactors. The system having the highest benefit of finance, environment, and energy was suggested.

Both AHRs could load at the maximum of OLR and shortest HRT were 7.5 kgCOD/m^3.d and 10 days, respectively, with high performance and stability for POME wastewater treatment. This condition was suitable for POME treatment without raw POME dilution process. Therefore, the installation of wastewater treatment plants was composed of the biogas and electricity production plants for mesophile (35 ºC) and thermophile (55 ºC) for this operating condition as a case study. Plants configuration were shown in Figure 4.20. The cooling pond was used for cooling wastewater temperature to 55 °C for thermophilic treatment plant and 35 °C for mesophilic treatment plant. The AHR was covered with insulator and non-covered with insulator for thermophilic and mesophilic treatment plants respectively. Scrubber was used for the biogas treatment unit for hydrogen sulfide removal. The electricity production system was included with generator and grid system.

Thermophilic and mesophilic wastewater treatment plants were designed on the condition of OLR 7.5 kgCOD/m^3.d, HRT 10 days, which feeding POME 600 m^3/day as shown in Table 4.11. The mesophilic and thermophilic tretmant plants was designed by using the equation (A6) and (A7), as shown in Appendix B. At this condition the reactor volume of the both treatment plants was 7,200 m^3. The thermophilic AHR was covered with 1,705 m^2 of insulator for insulated heat transfer from inside the reactor to the environment. The cost of fiberglass insulator installation was calculated by the equation (A8) and shown in the Table A11. Generally, POME was fed out from the palm oil production process with the temperature of 80 – 90 °C, the cooling pond was required for POME temperature cool down to 35 °C and 55 °C before feeding into mesophilic AHR and thermophilic AHR, respectively. The completely calculation for system analysis was shown in Appendix B.

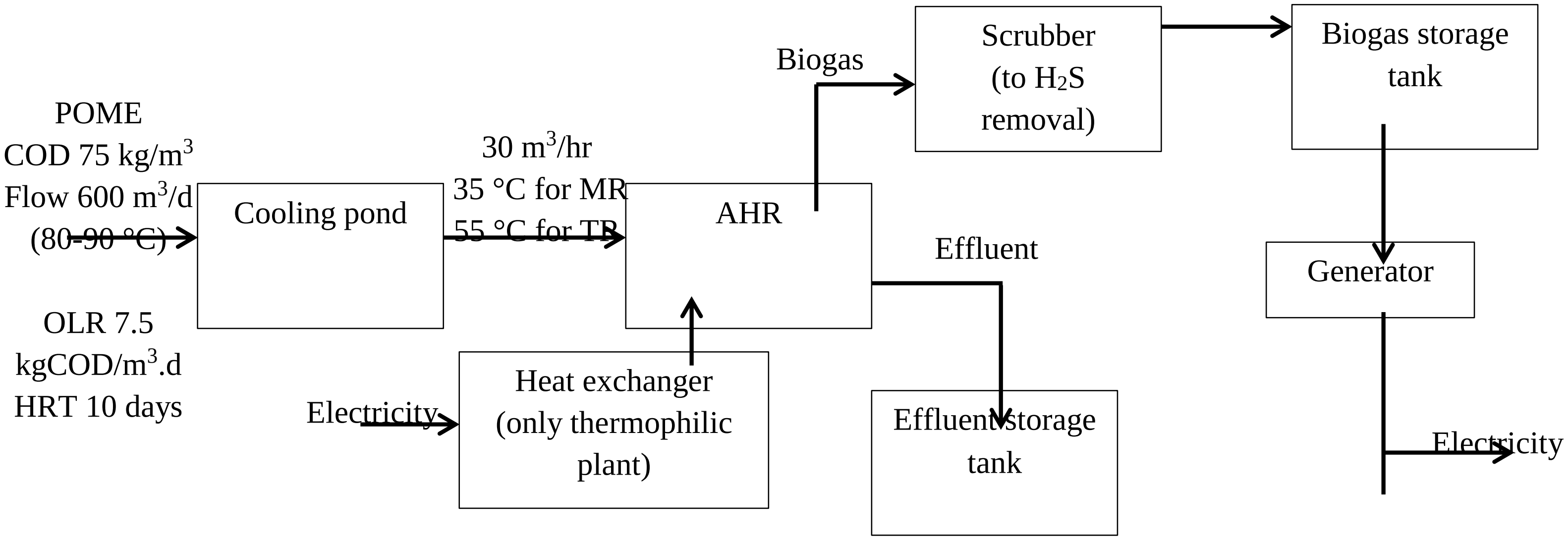

Figure 4.20 Mesophilic and thermophilic anaerobic treatment plant layouts

A heat exchanger is necessary for thermophilic plants in controlling the temperature inside the reactor when the palm oil production plant was shut down. Therefore, electric boiler was used for temperature control inside the thermophilic reactor at 55 ºC. During palm oil production plant was shut down, 10 kW of the electric boiler was operated 24 hour for every day. The period of palm oil production plant shutting down was assumed to 60 days for this study. For thermophilic reactor, wastewater inside the reactor was circulated through the outside heat exchanger with 0.09 kg/s or 8 m^3/day of wastewater flow rate for controlling the temperature inside the reactor at 55 ºC. The electric boiler was designed as the outside heat exchanger for thermophilic reactor temperature controller. The electric boiler was designed on an assumption as shown in Figure 4.21 and the calculation was shown in appendix B, by using the equation (A4), and (A5). The electric boiler was operated 24 hr/day. Therefore, the electric boiler was consumed electricity approximately 240 kWh/day. The plant's performance of thermophilic treatment plant was slightly higher than mesophilic treatment plant, which biogas productions of the both plants were 15,517 and 16,552 m^3/day for mesophilic and thermophilic treatment plants respectively. The electricity production was 35,689 kWh and 38,070 kWh, respectively.

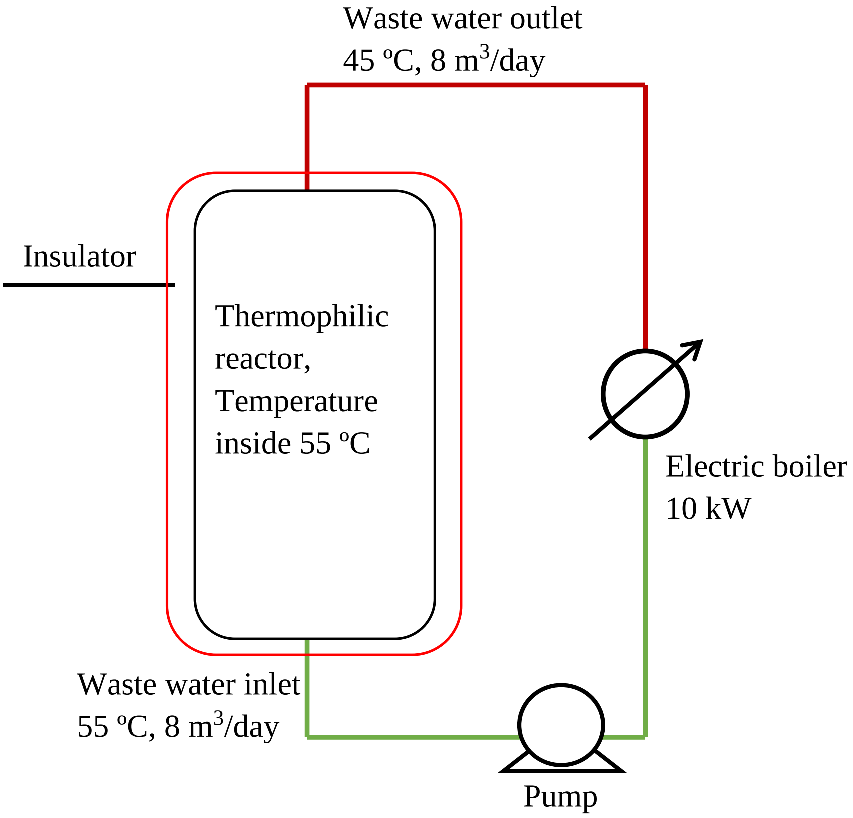

Figure 4.21 Temperature control for thermophilic reactor system

Table 4.11 Mesophilic and thermophilic treatment plant design

Item	Mesophilic plant	Thermophilic plant
AHR		
Working volume (m^3)	6,000	6,000
Reactor volume (m^3)	7,200	7,200
Reactor diameter (m)	21.42	21.42
Reactor high (m)	20.00	20.00
Insulator (m^2)	-	1,705
Heat exchanger (kW)	-	10
Cooling pond (m^3)	3,000	2,500
Biogas storage tank (m^3)	4,000	3,800
Scrubber (m^3)	1,500	1,500
Generator system (MW)	2	2

Table 4.12 Mesophilic and thermophilic treatment plant performance

Performance	Mesophilic plant	Thermophilic plant
Biogas yield ($m^3_{biogas}/kgCOD_{removed}$)	0.40	0.43
COD removal efficiency (%)	86	85
Biogas production (m^3/day)	15,517	16,552
Electricity production (kWh/day)*	35,689	38,070

*; 1 m^3 of biogas (70 % of methane) was produced 2.3 kWh of electricity

4.4.1 Financial analysis

A financial analysis was conducted for investment costs, which were wastewater treatment system, biogas and electricity production systems as well as construction plant and operating and maintenance costs. Table 4.13 was shown the details of investment cost, which consisted of installation, construction and equipment cost including operating and maintenance cost of the both wastewater treatment plants. The overall investment cost was 90.1 million baht for thermophilic AHR, which included insulator and electric boiler and and 89.6 million baht for mesophilic AHR, respectively. The thermophilic treatment plant was required the electricity for electric boiler operation. There are 14,400 kWh for 60 days of electric boiler operation in year, as shown in appendix B, Table A16. The operating and maintenance cost were 6.1 and 6.0 million baht per year for thermophilic and mesophilic treatment plants, respectively. The benefits of the both plants were shown in Table 4.14.There are payback period (PP) was 2 years, internal rate of return (IRR) was 42 and 45%, and net present value (NPV) was 189 and 208 million baht for mesophilic and thermophilic treatment plants, respectively with 10% of discount rate as shown in Table 4.15, and there are cash flow diagram as shown in Table 4.16 and 4.17. It can be noted that, thermophilic plant was recommended for installation of wastewater treatment plant to investor. The higher biogas production of the thermophilic treatment plant had a higher investment index, than did the mesophilic treatment plant.

Table 4.13 Mesophilic and thermophilic wastewater treatment plant costs

Item	Mesophilic plant	Thermophilic plant
AHR (baht)	30,000,000	30,000,000
Cooling pond (baht)	12,000,000	10,000,000
Fiberglass insulator (baht)	-	2,500,000
Heat exchanger (baht)	-	100,000
Biogas system (baht)	7,300,000	7,400,000
Electricity system with grid (baht)	40,000,000	40,000,000
Operating cost (baht /year)	2,058,000	2,108,000
Maintenance cost (baht /year)	3,980,000	4,000,000

Table 4.14 Mesophilic and thermophilic wastewater treatment plant benefits

Product	Mesophilic plant	Thermophilic plant
Biogas (m^3/day)	15,517	16,552
Electricity (kWh/year)	10,421,217	11,116,323

Table 4.15 Financial analysis

Index	Mesophilic plant	Thermophilic plant
Payback period (PP)	2 years	2 years
Internal rate of return (IRR)	42%	45%
Net present value (NPV)	189,000,000 baht	208,000,000 baht

Table 4.16 Mesophilic treatment plant cash flow diagram (Unit in million baht)

Item	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Invesment cost																
AHR installation	30.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cooling pond	12.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogas system	7.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity system	40.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Overall invesment cost	89.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Operating Maintenance cost																
Operating cost	0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Maintenance cost	0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Overall cost	89.6	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Income																
Electricity sales	0	43.8	43.8	43.8	43.8	43.8	43.8	43.8	40.6	40.6	40.6	40.6	40.6	40.6	40.6	40.6
Overall income	0	43.8	43.8	43.8	43.8	43.8	43.8	43.8	40.6	40.6	40.6	40.6	40.6	40.6	40.6	40.6
Net Cash-flow	-89.6	37.7	37.7	37.7	37.7	37.7	37.7	37.7	34.6	34.6	34.6	34.6	34.6	34.6	34.6	34.6
Accumulated	-89.6	-51.8	-14.1	23.6	61.4	99.1	136.8	174.6	209.2	243.8	278.4	313.0	347.6	382.2	416.8	451.4
Dicount factor	1.0	0.9	0.8	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2
NPV	-89.6	34.3	31.2	28.4	25.8	23.4	21.3	19.4	16.1	14.7	13.3	12.1	11.0	10.0	9.1	8.3

Table 4.17 Thermophilic treatment plant cash flow diagram (Unit in million baht)

Item	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Invesment cost																
AHR installation	30.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cooling pond	10.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Insulator	2.4	0	0	0	0	0	0	0	2.4	0	0	0	0	0	0	0
Electric boiler	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogas system	7.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity system	40.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Overall invesment cost	90.1	0	0	0	0	0	0	0	2.4	0	0	0	0	0	0	0
Operating																
Maintenance cost																
Operating cost	0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Maintenance cost	0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Overall cost	90.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	8.5	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Income																
Electricity sales	0.0	46.7	46.7	46.7	46.7	46.7	46.7	46.7	43.4	43.4	43.4	43.4	43.4	43.4	43.4	43.4
Overall income	0.0	46.7	46.7	46.7	46.7	46.7	46.7	46.7	43.4	43.4	43.4	43.4	43.4	43.4	43.4	43.4
Net Cash-flow	-90.1	40.6	40.6	40.6	40.6	40.6	40.6	40.6	34.8	37.2	37.2	37.2	37.2	37.2	37.2	37.2
Accumulated	-90.1	-49.5	-8.9	31.7	72.2	112.8	153.4	194.0	228.8	266.0	303.3	340.5	377.8	415.0	452.2	489.5
Dicount factor	1.0	0.9	0.8	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2
NPV	-90.1	36.9	33.5	30.5	27.7	25.2	22.9	20.8	16.2	15.8	14.4	13.1	11.9	10.8	9.8	8.9

4.4.2 Environmental analysis

In this section, two scenarios with biogas recovery by utilization for electricity production and without biogas recovery were applied to the environmental analysis. Environmental analysis in this study was scoped and analyzed on the wastewater treatment by determination of organic waste (COD) removal and the amount of greenhouse gas (GHG) emission and reduction. The system boundary was divided into two scenarios. The first scenario (scenario 1) was the case of the utilization of biogas, which used for electricity production. For this scenario, all of methane gas production was used for electricity production by generator. The total GHG emissions were emitted from CO_2 emission from anaerobic reactor and CO_2 emission from generator. The second scenario (scenario 2) was the case of without the utilization or recovery of biogas. For this scenario, the total GHG emissions were emitted from anaerobic reactor, which included CH_4 and CO_2 emissions. The GHG emissions were reported as CO_2 equivalent. The first and second scenarios were investigated on the total GHG emissions/ reduction in case of with and without the biogas recovery and utilization for palm oil treatment reactor at mesophilic and thermophilic conditions.

4.4.2.1 Removal of organic carbon pollutants

The degradation of POME was analyzed from the total amount of organic material (COD) in the POME removal from the AHR by using the following equation:

$$\mathrm{TOW_{ind}}\left(\frac{\mathrm{kgCOD}}{\mathrm{yr}}\right) = \mathrm{Q_{POME}} \times \mathrm{D_{ind}} \times \mathrm{DS_{ind}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(4)$$

Where;

TOW_{ind} = Total industrial organic wastewater removal in kg COD/ yr

Q_{POME} = Wastewater generation in m^3/ year

D_{ind} = Industrial organic components in kg COD/ m^3 wastewater

DS_{ind} = Fraction of industrial degradable organic components, removed as sludge and biogas

Equation (4) was calculated on the assumption that POME wastewater was generated 210,240 m^3/ year, COD concentration of POME was 75 kg/ m^3, and COD removal efficiency was 86 and 85 % for mesophilic and thermophilic AHRs, respectively. The total amount of organic waste removal from mesophilic and thermophilic AHRs were shown in Table 4.18. If without anaerobic treatment reactor, organic carbon pollutant will discharge to environment about 15,768 ton COD/year. With mesophilic and thermophilic AHRs, 13,560 and 13,400 ton COD/year of the total organic waste was removed, respectively. These results were demonstrated that mesophilic condition was the total industrial organic wastewater removal slightly higher than thermophilic condition about 1.18%.

Table 4.18 Total industrial organic wastewater removal

Parameter	MR	TR
Wastewater generated (m^3/ year)	210,240	210,240
D_{ind} (kg COD/ m^3)	75	75
Initial organic loading (ton COD/ yr)	15,768	15,768
DS_{ind}	0.86	0.85
TOW_{ind} (kg COD/ yr)	13,560,480	13,402,800
TOW_{ind} (ton COD/ yr)	13,560	13,400

4.4.2.2 GHG emissions

An environmental analysis was conducted on the amount of GHG emissions with Scenarios 1 and 2 were investigated. The biogas that produced from the AHR was included approximately by 70% of CH_4 and 30% of CO_2. The amount of GHG emissions were calculated from the results of methane and carbon dioxide gas productions of this study. The results were analyzed and compared to the GHG emissions from calculation of IPCC equation for industrial wastewater [30] as shown in the equation (6) and (7). Step of GHG emission calculator were shown as below.

Step 1: Calculated GHG emissions from IPCC equation.

$$\mathrm{GHG}_{\mathrm{biogas}\,(i)} = \mathrm{GHG}_{\mathrm{CH_4}(i)} + \mathrm{GHG}_{\mathrm{CO_2}(i)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

$$\mathrm{GHG}_{\mathrm{CH_4}(i)} = \mathrm{Q}_{\mathrm{POME}} \times \mathrm{COD}_{\mathrm{removal}} \times \mathrm{Bo}_{\mathrm{CH4}} \times \mathrm{MCF} \times \mathrm{GWP\_CH_4} \dots\dots (6)$$

$$\mathrm{GHG}_{\mathrm{CO_2}(i)} = \mathrm{Q}_{\mathrm{POME}} \times \mathrm{COD}_{\mathrm{removal}} \times \mathrm{Bo}_{\mathrm{CO2}} \times \mathrm{MCF} \dots\dots\dots\dots\dots\dots\dots\dots (7)$$

Step 2: Calculated GHG emissions from the results of this study.

Table 4.19 showed the volume of biogas, methane gas and carbon dioxide gas production from mesophilic and thermophilic AHRs. The GHG emissions from the AHR of this study were calculated by using the Equation (9-11).

Table 4.19 Biogas, CH4 and CO_2 production from MR and TR of this study

Gas production	MR	TR
Biogas (m^3/day)	15,517	16,552
CH_4 concentration (%)	69.87	70.35
CO_2 concentration (%)	30.13	29.65
CH_4 production (m^3/day)	10,842	11,715
CO_2 production (m^3/day)	4,675	4,908

In Table 4.19, the composition of biogas production was used for GHG emission calculation. The GHG emission were calculated by using equations (9), (10), and (11).

$$\mathrm{GHG_{biogas}} = \mathrm{GHG_{CH_4}} + \mathrm{GHG_{CO_2}} \ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$$\mathrm{GHG_{CH_4}} = \mathrm{CH_4\ production} \times \ \rho_{\mathrm{CH_4}} \times \mathrm{GWP\_CH_4} \ldots\ldots\ldots (10)$$

$$\mathrm{GHG_{CO_2}} = \mathrm{CO_2\ production} \times \rho_{\mathrm{CO_2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Step 3: Compared the amount of GHG emissions between IPCC equation and from the results of this study.

Step 4: Calculated GHG emissions from electricity production.

The GHG emissions from electricity production were approximated by using the equations (12) and using GHG emission factor for electricity production with biogas as a fuel [41].

$$\mathrm{GHG_{electricity}} = \mathrm{Electricity\ production}\ \left(\frac{\mathrm{MWh}}{\mathrm{year}}\right) \times 0.524 \left(\frac{\mathrm{tonCO_{2e}}}{\mathrm{MWh}}\right) \ldots\ldots\ldots.. (12)$$

Step 5: Compared the amount of GHG emissions of Scenarios 1 and 2.

Scenario 1: All of biogas was used for electricity production. Total GHG emission of treatment reactor and generator were calculated

Scenario 2: Total GHG emission of treatment reactor, which CH_4 and CO_2 were included, was calculated.

The data used and results of the step for GHG emissions calculator were shown in Tables 4.20-4.21. Not more than 20% of difference between the amount of GHG emission of IPCC equation calculation and GHG calculation from the results of this study. This difference was not more than the uncertainty estimates value from IPCC equation (IPCC, 2006). The scenario 1 with biogas recovery and utilization for electricity production, the total GHG emission was 8,163 and 8,662 ton CO_{2e}/ year for mesophilic and thermophilic reactors, respectively. The scenario 2 without biogas recovery and utilization, the total GHG emission was 54,938 and 58,939 ton CO_{2e}/ year for mesophilic and thermophilic reactors, respectively. AHR was the high-rate reactor for biogas production. The potential of GHG reduction in this study was calculated by comparison of the scenario 1 (with biogas utilization) with scenario 2 (without biogas utilization). The potential of GHG reduction for mesophilic and thermophilic reactors were 46,775 and 50,227 ton CO_{2e}/ year, respectively. It can be noted that, thermophilic reactor was 7.38% of the performance of GHG reduction rate higher than mesophilic reactor. Therefore, thermophilic condition was more interested than mesophilic condition in term of environmental analysis.

Table 4.20 Data used in the calculations for environmental analysis

Parameter	Description	Unit	Value
ρ_{CH_4}	Density of methane gas	$kgCH_4/m^3$	0.66[a]
ρ_{CO_2}	Density of carbon dioxide gas	$kgCO_2/m^3$	1.98[a]
Bo_{CH4}	CH_4 unit of organic compounds	$kgCH_4/kgCOD$	0.21[b]
Bo_{CO2}	CO_2 unit of organic compounds	$kgCO_2/kgCOD$	0.21[b]
CH_4 production	CH_4 production from AHR	m^3/day	Table 4.19
CO_2 production	CO_2 production from AHR	m^3/day	Table 4.19
$COD_{removal}$	COD removal by AHR	$kgCOD/m^3$	Cal.[c]
D_{ind}	Industial organic component	$kgCOD/m^3$	Table 4.18
DS_{ind}	Fraction of organic degradable	%	Table 4.18
Electricity	Electricity production from biogas	MWh/year	Table 4.12
GHG_{biogas}	GHG emission from the study	$tonCO_{2e}$/year	Table 4.21
$GHG_{biogas(i)}$	GHG emission from the IPCC	$tonCO_{2e}$/year	Table 4.21
$GHG_{electricity}$	GHG emission from generator	$tonCO_{2e}$/year	Table 4.21
GHG_{CH4}	GHG emission from CH_4 of the study	$tonCO_{2e}$/year	Table 4.21
$GHG_{CH4(i)}$	GHG emission from CH_4 of IPCC	$tonCO_{2e}$/year	Table 4.21
GHG_{CO2}	GHG emission from CO_2 of the study	$tonCO_2$/year	Table 4.21
$GHG_{CO2(i)}$	GHG emission from CO_2 of IPCC	$tonCO_2$/year	Table 4.21
GWP_CH_4	Global warming potential of methane	$kgCO_{2e}/kgCH_4$	25[b]
MCF	Methane conversion factor of AHR	-	0.8[b]
Q_{POME}	Volume of POME generation	m^3POME/year	Table 4.18
TOW_{ind}	Total industrial organic waste removed	kgCOD/year	Table 4.18

[a] Welty et al., [42]
[b] IPCC [30]

Table 4.21 GHG emissions of mesophilic and thermophilic reactors

System	GHG emission (tonCO$_{2e}$/year)			
	Mesophilic reactor		Thermophilic reactor	
	IPCC [30]	This study	IPCC [30]	This study
Biogas production GHG_{CH_4} (A) GHG_{CO_2} (B)	 56,954 2,234	 52,235 2,703	 56,291 2,208	 56,102 2,837
Electricity production $GHG_{electricity}$ (C)	-	5,460	-	5,825
Total emission of Scenario 1 with biogas utilization (B+C)	-	8,163	-	8,662
Total emission of Scenario 1 without Biogas utilization (A+B)	59,188	54,938	58,499	58,939

4.4.3 Energy analysis

Energy production of thermophilic and mesophilic wastewater treatment plants was generated from biogas, which was about 70% of methane gas. Energy equivalent, which 1 m^3 of methane gas was equivalent to 39.4 MJ, of methane gas production was used for energy analysis. There are 3.4 and 3.1 million m^{3}CH$_4$/year for thermophilic and mesophilic treatment plants, respectively. There are energy equivalent produced from the processes 133,966 and 124,721 GJ/year for thermophilic and mesophilic treatment plants, respectively. Electricity production from mesophilic treatment plants was investigated only the production of biogas production. While, electricity production from thermophilic treatment plants was investigated on the production of biogas production and the electricity consumption for heating the inside reactor temperature during palm oil production plant shutting down. The gas generator used in this study for mesophilic or thermophilic systems had capacity 2 MW and thermal efficiency of generator 2.3 kWh/m^3 biogas with 70% methane. About 7.4% of energy production and 6.5% of electricity production from thermophilic treatment plant was higher than mesophilic treatment plant, as shown in Table 4.22.

Table 4.22 Energy analysis

Energy	Mesophilic plant	Thermophilic plant
Biogas (m^3/day)	15,517	16,552
Biogas (m^3/m^3 of POME.d)	26	28
CH_4 concentration (%)	69.87	70.35
Methane gas (m^3/year)	3,165,785	3,400,145
Energy production (GJ/year)	124,721	133,966
Electricity production (kWh/year)	10,421,217	11,101,923

The processes performance and stability of the thermophilic and mesophilic AHRs were not significantly different, but in terms of system analysis, the thermophilic wastewater treatment plant had higher performance than mesophilic treatment plant at the financial and energy field, which were 10.28% of NPV of the thermophilic treatment plant higher than the NPV of the mesophilic treatment plant, 7.38% of GHG emission reduction rate and 7.4% of energy production and 6.5% of electricity production of thermophilic treatment plant was higher mesophilic treatment plant. While 1.18% of organic waste degradable performance of mesophilic was higher than thermophilic treatment plants. It can be noted that, although in term of system performance and stability of thermophilic condition not significant higher than mesophilic condition, but in term of system analysis, the thermophilic condition was the most interested to investment, and may be suggested to the investor with the higher of financial, environmental and energy benefit.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Anaerobic hybrid reactor (AHR) was operated under thermophilic (55 °C) and mesophilic (35 °C) conditions. The inoculum seed was obtained from mesophilic anaerobic cover lagoon POME treatment system and used as inoculum seeds for the mesophilic AHR. The inoculum seed for thermophilic AHR used acclimatized seed from mesophilic anaerobic cover lagoon by step increased 5 °C/day until up to 55 °C. The consecutive operating condition of mesophilic and thermophilic AHRs from OLR 1.2 gCOD/l.d and HRT 20 d until OLR 11.5 gCOD/l.d and HRT 5.3 d were successful operation within 193 days. Both AHRs were operated well with high performance efficiency and stability at OLR 7.5 gCOD/l.d and HRT 5.3-10 d.

The mesophilic AHR stability, which increased OLR from 1.2 gCOD/l.d to 7.5 gCOD/l.d and HRT reduced from 20 days to 10 days, pH was stable with pH 7 – 8 and the ratio of TVA/Alk was lower than 0.5. In addition, the increase of OLR from 7.5 to 11.5 gCOD/l.d and HRT shorten from 10 to 5.3 days, the pH was step decreased until lowest at 6.66 for OLR 11.5 gCOD/l.d and HRT 5.3 days and the ratio of TVA/Alk was 1.06. After over shock loading of OLR 11.5 gCOD/l.d and HRT 5.3 days, the mesophilic AHR was stopped feed 5 days and was operated under OLR 7.5 gCOD/l.d and HRT 10 days up to 21 days, before the AHR stability was recovered to the normal condition. High performance of mesophilic AHR at OLR 7.5 gCOD/l.d and HRT 5.3-10 d was 80-86% COD removal and 10-13 l/d of methane production with 0.30-0.35 $lCH_4/gCOD_{removed}$ of methane yield. For SMA at the sludge zone was slightly lower than packed zone, while SGU at the sludge zone was slightly higher than packed zone. It can be note that most of bacteria at the sludge zone were non-methanogens and at the packed zone was methanogens.

The thermophilic AHR stability, which increased OLR from 1.2 to 7.5 gCOD/l.d ant reduced HRT from 20 to 10 days was stable with pH 7 – 8 and the ratio of TVA/Alk was lower than 0.5.The increasing of the thermophilic AHR OLR from 7.5 to 11.5 gCOD/l.d and reduced HRT from 10 to 5.3 day, the pH was decreased until lowest at OLR 11.5 gCOD/l.d and HRT 5.3 days was 6.88 and the ratio of TVA/Alk was 0.72. After OLR 11.5 gCOD/l.d and HRT 5.3 days, the thermophilic AHR was operated under the condition of OLR 7.5 gCOD/l.d and HRT 10 days up to 14 days, before the AHR stability was normal condition.

High performance of the thermophilic AHR in COD removal, which was 80-85%, and methane production, which was 13-15 l/d, with high methan yield, which was 0.35-0.40 $lCH_4/gCOD_{removed}$, were found at the condition of OLR 7.5 gCOD/l.d and HRT 5.3-10 d. Microbial activities of acidogens and methanogens were highest 2.78 $gCOD_{glucose}/gVSS.d$ and 0.24 $gCOD_{methane}/gVSS.d$ at the condition of OLR 7.5 gCOD/l.d and HRT 10 days. For SMA at the sludge zone was slightly lower than packed zone, while SGU at the sludge zone was slightly higher than packed zone.

According to the high performance, stability, and microbial activity of mesophilic and thermophilic AHRs, the OLR 7.5 gCOD/l.d and HRT 5.3-10 d was the maximum OLR and shortest HRT for both AHRs to treat and produce biogas from raw POME. A thermophilic reactor achieved a reactor performance slightly higher than mesophilic reactor with the reactor stability being slightly more stable. When more loading higher OLR than 7.5 to 11.5 gCOD/l.d at HRT 5.3 d, both reactors were over shock load by $pH < 7$, TVA/Alk ratio > 0.5 and methane yield < 0.2 $lCH_4/gCOD_{removed}$ and then stop feeding for 5 days. After that feeding back at OLR 7.5 gCOD/l.d and HRT 10 d, thermophilic and mesophilic AHRs can recover to the normal condition at $pH > 7$, TVA/Alk ratio closed to 0.6 and methane yield > 0.30 $lCH_4/gCOD_{removed}$ within 14 and 21 days, respectively. For recovery period, thermophilic reactor was slightly more the process flexibility than mesophilic reactor.

Therefore, the condition of OLR 7.5 gCOD/l.d and HRT 10 days was used for system analysis in the full scale mesophilic and themophilic AHRs by receiving 600 m^3/d of raw POME. The system analysis was analyzed for the benefits of financial, environment, and energy production. The overall investment cost for mesophilic and thermophilic treatment systems including biogas utilization for electricity production was 89.6 and 90.1 million baht, respectively. The operating cost and maintenance cost were 2.06 and 3.98 million baht for mesophilic system and 2.11 and 4.00 million baht for thermophilic system, respectively. There are payback period (PP) was 2 years, internal rate of return (IRR) was 42 and 45%, and net present value (NPV) was 189 and 208 million baht for mesophilic and thermophilic treatment plants, respectively with 10% of discount rate. The thermophilic treatment plant was recommended to investment, there are higher than 10.28% of NPV for financial analysis, 7.4% of energy production and 6.5% of electricity production. In terms of environmental analysis of organic pollutant removal, the AHR can remove organic carbon pollutant from POME of mesophilic and thermophilic AHRs around 13,560 and 13,400 ton COD/yr, respectively. In addition, mesophilic and thermophilic AHRs have capability for

GHG reduction 46,775 and 50,277 ton CO_2e/ yr by comparing with the system without biogas recovery and utilization. The environmental analysis of GHG reduction found that the thermophilic treatment plant was slightly more than mesophilic treatment plant 7.38% of CO_{2e}.

5.2 Recommendations

For future studies may be suggested to use inoculum seeds, which originate from thermophilic digester and having the wide range operated temperature of mesophilic to thermophilic temperature with high reactor performance efficiency and stability with high methanogenic activity. Furthermore, microbial community was also importance for explain the phenomenal during each operating condition inside the reactor. The molecular techniques may by greatly increase more understanding of microbial diversity and functional inside the reactor environment during each operating condition.

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APPENDIX A

Results data

1. Reactor stability

Table A1 Mesophilic and thermophilic reactor stability

Condition	OLR (gCOD/l.d)	HRT (Days)	MR				TR			
			pH	Alk (mg/l)	TVA (mg/l)	TVA/Alk	pH	Alk (mg/l)	TVA (mg/l)	TVA/Alk
1	1.2	20	7.63	2,563.18	1,080.61	0.42	7.73	2,544.06	1,220.15	0.48
2	2.0	15	7.58	2,632.09	1,101.34	0.42	7.79	2,570.84	1,462.09	0.57
3	2.6	15	7.76	2,731.67	1,073.96	0.39	7.76	2,950.00	1,235.84	0.42
4	2.6	10	7.60	3,142.84	1,316.67	0.42	7.72	3,348.84	1,520.37	0.45
5	3.5	10	7.55	3,397.16	1,624.76	0.48	7.58	3,287.23	1,535.00	0.47
6	4.5	10	7.46	3,504.17	1,539.17	0.44	7.71	3,425.42	1,592.70	0.46
7	5.5	10	7.50	3,716.37	1,341.67	0.36	7.11	3,387.43	1,488.64	0.44
8	6.5	10	7.57	3,971.73	1,583.34	0.40	7.68	3,768.45	1,876.09	0.50
9	7.5	10	7.50	4,087.50	1,898.20	0.46	7.70	3,976.64	1,970.14	0.50
10	7.5	5.3	7.41	3,634.54	2,038.74	0.56	7.61	2,880.67	1,777.27	0.62
11	8.5	5.3	7.36	3,190.00	2,674.50	0.84	7.44	2,902.00	1,940.44	0.67
12	9.5	5.3	7.04	2,949.67	2,674.50	0.91	7.35	2,765.00	2,218.44	0.80
13	10.5	5.3	6.76	2,941.04	2,774.00	0.94	7.09	2,737.00	2,360.34	0.86
14	11.5	5.3	6.58	2,633.37	2,786.67	1.06	6.88	2,459.67	2,699.34	1.10

2. Reactor performance

Table A2 Mesophilic and thermophilic reactor performance

Condition	OLR (gCOD/l.d)	HRT (Days)	COD removal (%)		Methane yield (l_{CH4}/$gCOD_{removal}$)	
			MR	TR	MR	TR
1	1.2	20	86.89	75.48	0.16	0.20
2	2.0	15	90.75	84.30	0.17	0.17
3	2.6	15	92.39	87.84	0.30	0.24
4	2.6	10	83.48	78.89	0.24	0.20
5	3.5	10	89.48	82.78	0.24	0.25
6	4.5	10	90.75	87.11	0.29	0.29
7	5.5	10	92.25	91.91	0.23	0.25
8	6.5	10	88.29	87.41	0.25	0.30
9	7.5	10	85.78	84.80	0.30	0.34
10	7.5	5.3	79.27	80.80	0.35	0.40
11	8.5	5.3	68.59	70.91	0.29	0.38
12	9.5	5.3	62.91	65.56	0.22	0.30
13	10.5	5.3	59.36	63.83	0.14	0.26
14	11.5	5.3	53.13	61.01	0.12	0.15
15	7.5	10	86.06	89.22	0.33	0.37

3. Microbial activity

Table A3 Concentration of seeds at each operating condition (VSS)

Condition	Sludge zone (gVSS/l)		Packed zone (gVSS/l)		Total	
	TR	MR	TR	MR	TR	MR
Initial	20.10	20.10	0.00	0.00	20.10	20.10
OLR 3.5 HRT 10	39.05	36.69	12.16	16.39	51.21	53.08
OLR 5.5 HRT 10	60.87	50.22	12.27	18.17	73.14	68.39
OLR 7.5 HRT 10	120.62	109.83	18.66	21.11	139.28	130.94
OLR 7.5 HRT 5.3	110.13	98.45	19.36	23.78	129.49	122.23
OLR 11.5 HRT 5.3	109.00	87.14	17.87	11.96	126.87	99.10

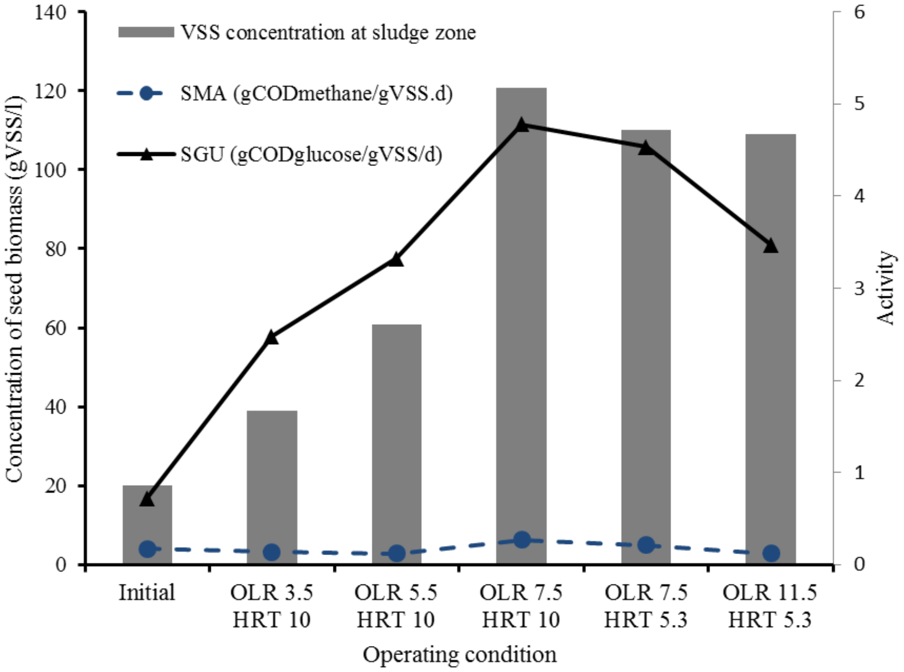
Table A4 Methanogenic activity

Condition	Sludge zone ($gCOD_{methane}/gVSS.d$)		Packed zone ($gCOD_{methane}/gVSS.d$)	
	TR	MR	TR	MR
Initial	0.17	0.26	-	-
OLR 3.5 HRT 10	0.14	0.11	0.19	0.16
OLR 5.5 HRT 10	0.12	0.11	0.18	0.23
OLR 7.5 HRT 10	0.27	0.19	0.22	0.25
OLR 7.5 HRT 5.3	0.21	0.14	0.21	0.23
OLR 11.5 HRT 5.3	0.12	0.09	0.16	0.16

Table A5 Acidogenic activity

Condition	Sludge zone (gCOD$_{glucose}$/gVSS.d)		Packed zone (gCOD$_{glucose}$/gVSS.d)	
	TR	MR	TR	MR
Initial	0.72	0.77	-	-
OLR 3.5 HRT 10	2.48	1.05	2.33	1.35
OLR 5.5 HRT 10	2.32	2.23	3.11	2.01
OLR 7.5 HRT 10	2.78	2.32	3.22	2.89
OLR 7.5 HRT 5.3	2.53	2.08	2.01	2.16
OLR 11.5 HRT 5.3	2.47	1.83	1.98	1.94

Sludge zone



Packed zone

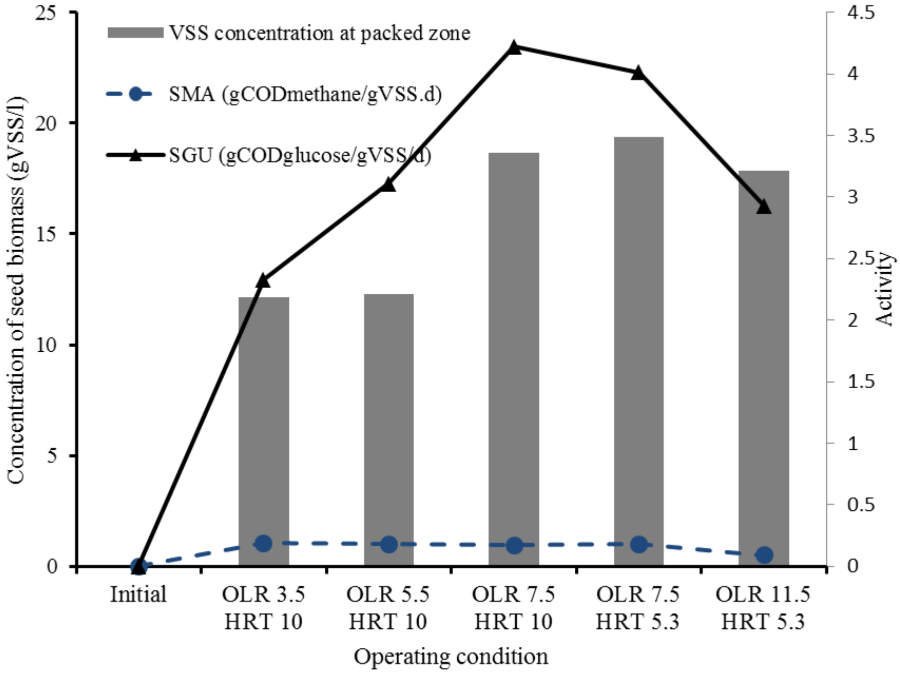
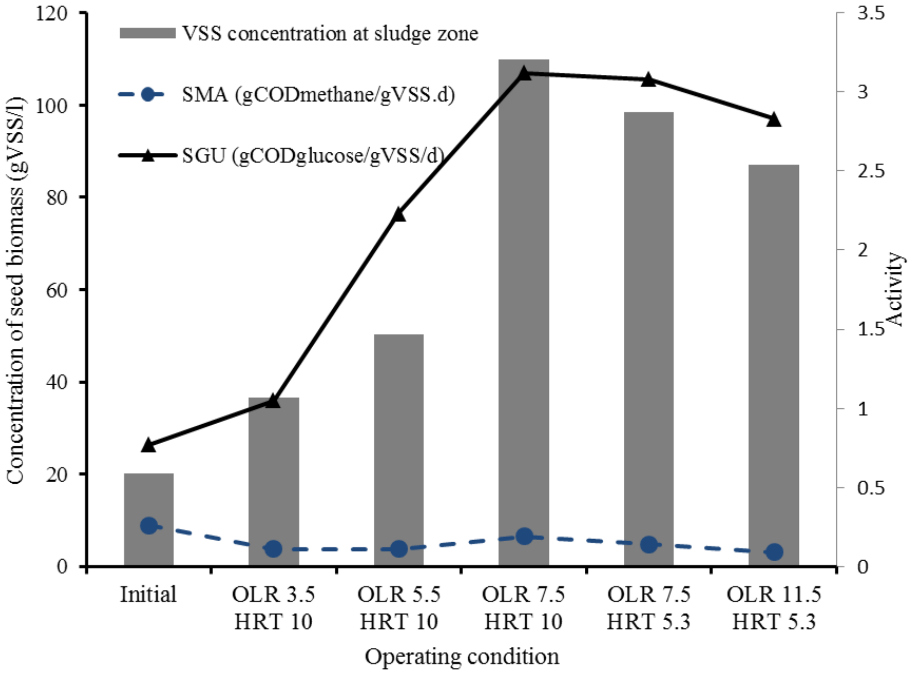


Figure A1 Biomass concentrations, SGU, and SMA at packed and sludge zones of thermophilic reactor

Sludge zone



Packed zone

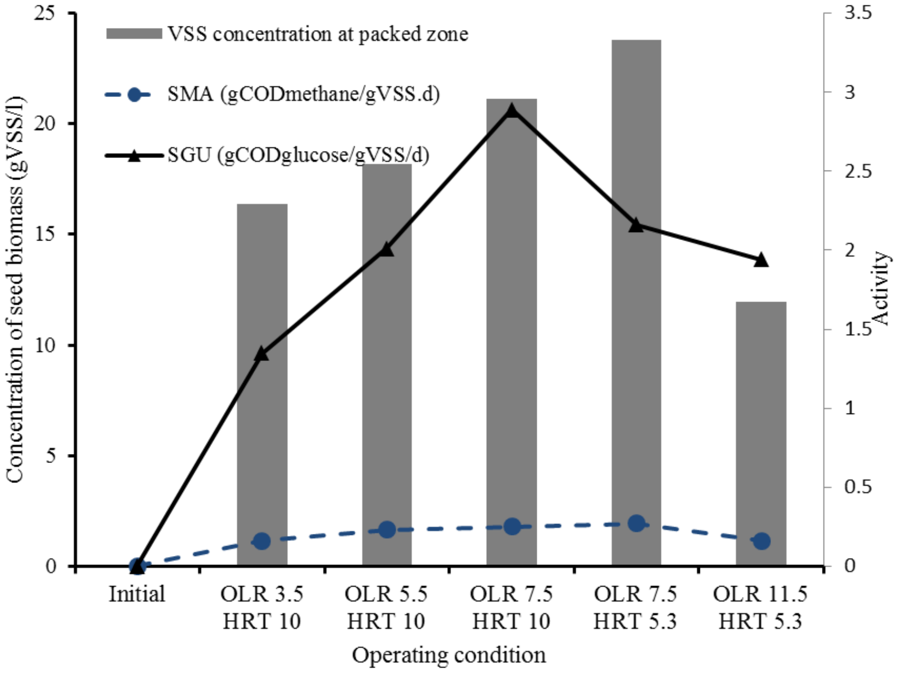


Figure A2 Biomass concentrations, SGU, and SMA at packed and sludge zones of mesophilic reactor

APPENDIX B

Analytical methods

Gas composition

Methane in biogas was analyzed by GC (Shimadzu, Class-GC 9A). GC was specification following parameters below:

Column ID and length: Porapak-N-80/100, 1/8 inch
Detector : TCD
Current bridge : 100mA
Carrier gas : Helium
Column temperature : 70 ºC
Detector temperature : 120 ºC
Injection temperature : 120 ºC

Biogas sample was collected by syringe (gas type) 10 ml from U-tube, which was installed at the gas production line of the reactor. Biogas was injected in to GC and gas composition was reported by integrator of Shimadzu Model C-R3A.

Alkalinity and Total volatile acid

The sample of effluent from both reactors was collected and analyzed for Alk and TVA. Alk was analyzed by titration with 0.05 N H_2SO_4 until pH was 4.0. Volumes of H_2SO_4 were calculated for Alk. This sample was heated 2 – 3 minutes and continuously titrated with 0.05 N NaOH until pH was 7.0. The volume of NaOH was calculated for TVA.

COD

Samples of effluents from both reactors was collected and analyzed for COD, which as a total COD. Potassium permanganate ($KMnO_4$) was used for determination of COD with the effluent sample. The mixed of sample was refluxed digestion and was determined an organic substrate concentration by using spectrophotometer for determination of oxidant still remaining of the sample.

Total solid, suspended solid, and volatile suspended solid

Total solids were determined with both raw POME and effluent by drying the sample with the temperature of 105 ºC over 24 hr. After that, cool down the sample in desiccators. The weight of the sample was recorded. Suspended solid was analyzed by filtrated and dry 105 ºC over 24 hr. The weight of the sample was recorded as the suspended solid. Next, furnace this sample with the temperature of 550 ºC. The weight loss of the sample was recorded as the volatile suspended solid.

Oil and Grease

Hexane extraction method was analyzed for oil and grease in this research.

Statistical differences

The statistical differences was calculated on the theory of two hypotheses with 95% of dependability ($\lambda = 0.05$). Minitab software was used for the statistical differences in this research. The program was reported the results in form of P-Value. Typically, if two data have P-Value was lower than λ, both data was significant differences. P-Value of the reactors performance was shown in the Table below.

Table A6 P-Value of mesophilic and thermophilic reactor performance

Performance	P-Value
$COD_{removal}$	0.828
Methane production	0.232
Methane yield	0.261

Specific methanoganics activity (SMA)

SMA was analyzed on the 100 ml of vial. In the vial was composed by seed and carbon source of bacteria for bacteria growth rate. The importance substrate for methanogens was acetic acid. There is 1.4 ml in sample vial 100 ml. Other substrates are shown in Table A7. The procedure of SMA analysis is shown in Figure A3. And SMA was calculation from Equation A1.

Table A7 Food for SMA analysis (Khemkhao et al., 2010)

Macro-Nutrient Solution	Value	Unit
$(NH_4)_2SO_4$	13.50	g/l
$MgSO_4$	9.00	g/l
$NaH_2PO_4H_2\ O$	7.55	g/l
$CaCl_2$	5.00	g/l
Nutrient solution	0.30	ml
Yeast extract granulated	0.01	g/l
Sodium acetate	1.40	g/l

$$\mathrm{SMA} = \frac{\mathrm{Slope}\ (\frac{\mathrm{ml_{CH_4}}}{\mathrm{day}})}{\mathrm{Seed\ in\ 100ml\ vial\ (gVSS)}} \times \frac{1\ \mathrm{gCOD_{CH_4}}}{350\ \mathrm{ml_{CH_4}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathrm{A1})$$

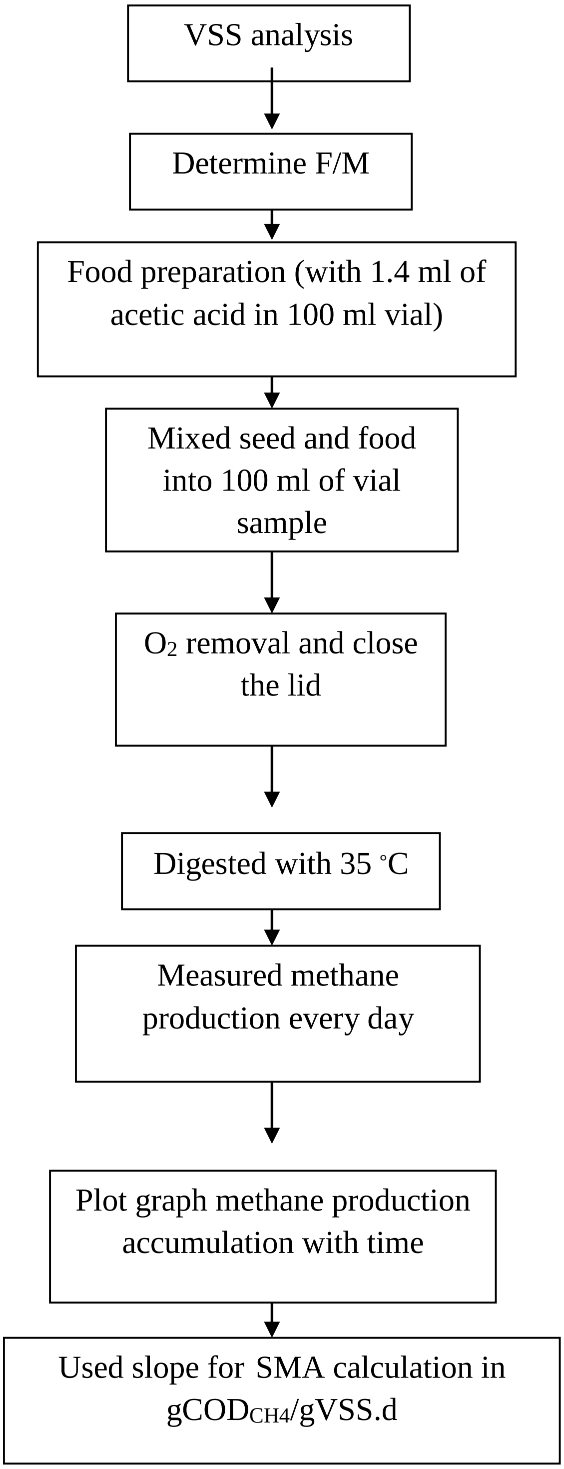


Figure A3 The procedure of SMA analysis

Specific Glucose Utilization (SGU)

SGU was analyzed on 100 ml of vial. The importance substrate for non-methanogens was glucose. There is 1 g/l of glucose in sample vial 100 ml. Other substrates are shown in Table A8. The procedure of SGU analysis is shown in Figure A4. And SGU was calculated from Equation A2.

Table A8 Food for SGU analysis (Khemkhao et al., 2010)

Macro-Nutrient Solution	Value	Unit
$(NH_4)_2SO_4$	13.5	g/l
$MgSO_4$	9	g/l
$NaH_2PO_4H_2O$	7.55	g/l
$CaCl_2$	5	g/l
Nutrient solution	0.3	ml
Yeast extract granulated	0.01	g/l
Glucose	1	g/l

$$\mathrm{SGU} = \frac{\mathrm{Slope}\ (\frac{\mathrm{g_{Glucose}/l}}{\mathrm{hr}})}{\mathrm{seed\ in\ 100\ ml\ vial\ (gVSS)}} \times \frac{\mathrm{24\ hr}}{\mathrm{day}} \times \frac{\mathrm{0.1065gCOD_{Glucose}}}{\mathrm{g_{Glucose}}} \ldots\ldots\ldots\ldots\ldots\ldots..\ \mathrm{(A2)}$$

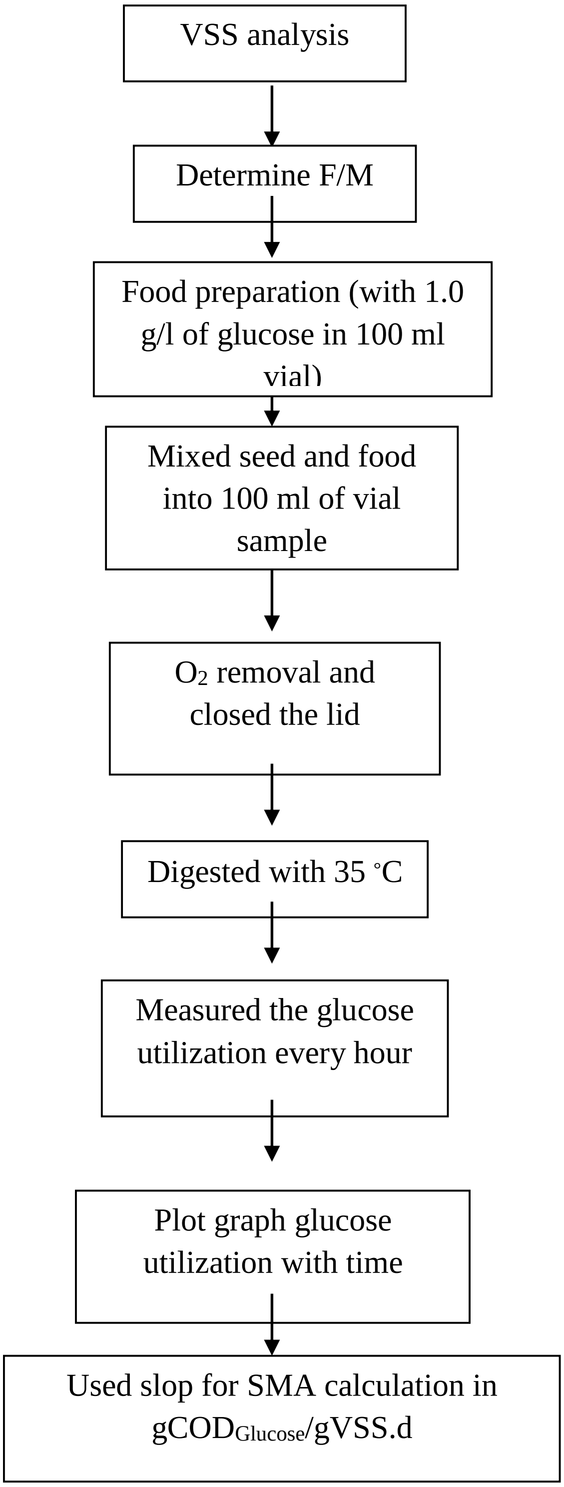


Figure A4 The procedure of SGU analysis

Standard temperature and pressure (STP)

Volume of gas production was reported on STP value. STP was calculated on standard temperature (0 ºC or 273 K) and pressure (100 kPa) condition. These volumes were calculated following the Equation A3.

$$\frac{T_1}{V_1} = \frac{T_2}{V_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(A3)$$

Reactor design for system analysis

Heat transfer from the temperature inside the thermophilic reactor to the environmental outside the reactor was calculated following the equation below.

$$Q_{loss} = \frac{KA}{L}(T_1 - T_2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(A4)$$

Where:

Q_{loss} = Heat loss (kW)

K = Thermal conductivity of insulator covered around the reactor (0.032 W/m.k)

A = Area of the reactor (m^2)

L = Thickness of the insulator (m)

T_1 = Temperature inside the reactor (K)

T_2 = Wall surface temperature (K)

Wastewater circulated flow rate was calculated following the equation below.

$$Q_{convection} = \acute{m}C_p(T_{1in} - T_{out}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(A5)$$

Where:

$Q_{convection}$= Q_{loss} (kW)

ḿ = Mass flow rate of wastewater (kg/s)

C_p = Heat capacity of wastewater (4.2 kJ/Kg.K)

T_{in} = Temperature inlet of the reactor (K)

T_{out} = Temperature outlet of the reactor (K)

The volume of AHR was calculated using the operating condition of OLR 7.5 gCOD/l.d and HRT 10 d using the equation below.

$$HRT = \frac{Volume_{reactor}(m^3)}{Waster\ water_{flow}(\frac{m^3}{day})} \ldots\ldots\ldots\ldots\ldots\ldots(A6)$$

The COD influent was calculated using the equation below. By assuming the raw POME was COD concentration about 70 – 80 gCOD/l.

$$\mathrm{OLR} = \frac{\mathrm{COD_{inf}}(\frac{\mathrm{gCOD}}{\mathrm{l}})}{\mathrm{HRT\ (day)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(\mathrm{A7})$$

The reactor volume requirement was 20% of the reactor working volume. There are 7,200 m^3 as shown in the table below. The mesophilic and thermophilic AHRs were designed on the assumption of the COD concentration of raw POME was 70-80 gCOD/l and the reactors was high 20 m.

Table A9 AHR diameter and operating conditions

Anaerobic hybrid reactor			
Operated			
OLR	=	7.5	gCOD/l.d
HRT	=	10	Days
POME flow	=	30	m^3/hr
	=	600	m^3/day
CODin	=	80	gCOD/l
Diameters			
Working volume	=	6,000	m^3
Reactor require	=	7,200	m^3
Reactor Diameter	=	21.42	m
Reactor high	=	20.00	m

Table A10 Performance of AHR

Reactor Performance		
Performances	MD	TD
Biogas yield (l_{biogas}/$gCOD_{removed}$)	0.40	0.43
COD Removed (%)	86	85
Biogas production (m^3/day)	15,517	16,552
Electricity production (1:2.3) (kWh)	35,689	38,070

A fiberglass insulator was used only in the thermophilic AHR. The cost of insulator was calculated by the assumption of 1 Ea of insulator was 2 in of thickness, 1,200 × 15,000 mm. of dimension. An amount insulator was calculated from the perimeter of the reactor (the perimeter of cylindrical), which included the surface of side and the top of the reactor.

$$\text{The perimeter of the reactor} = \pi rh + \pi r^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(\mathrm{A8})$$

Where:

r = The reactor radius (m)

h = The reactor height (m)

The cost of the jacket (4x8ft) was 600 baht/Ea.

The cost of the insulator was approximately 600 baht/m^3 (installation cost was included).

Table A11 Cost of fiberglass insulator installation for thermophilic reactor

Insulator for thermophilic AHR	=	1,345	m^2
	=	98	Ea
	=	372,400	Baht
Jacket	=	807,106	Baht
Construction	=	807,106	Baht
Total cost of insulator	=	1,986,611	Baht

3,000 and 2,500 m^3 of cooling pond were assumed for mesophilic and thermophilic treatment plants, respectively. The HRT of the cooling pond was assumed to be 1 day. The volume of the cooling pond was calculated follow the equation (A9), with safety factor 1.33 (33%). The cost of cooling pond was 3,071.43 Baht/m^3 (installation coast was included).

$$\text{Volume of Cooling pond}(\mathrm{m}^3) = \text{Flow rate}\left(\frac{\mathrm{m}^3}{\mathrm{day}}\right) \times \text{HRT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(\mathrm{A9})$$

Table A12 Cost of cooling pond

Cooling pond		MR		TR	
Price	=	3,071.43	Baht/m^3	3,071.43	Baht/m^3
	=	12,255,006	Bath	10,212,505	Bath
Safety factor	=	1.33		1.33	

The biogas storage tank was calculated on the volume of biogas production for the both treatment plants, by using the assumption of 1 m^3/hr was used 0.005 m^3 of Storage tank. The cost of the biogas storage tank was 100,000 baht/m^3 (including installation cost).

Table A13 Biogas storage tank design

Biogas system								
Biogas storage tank								
TR					MR			
Biogas	=	16,552	m^3/day		Biogas	=	15,517	m^3/day
Storage tank	=	4.138	m^3		Storage tank	=	3.87925	m^3
Storage tank price	=	100,000	Bath/m^3		Storage tank price	=	100,000	Baht/m^3
	=	413,800	Baht			=	387,925	Baht
Construction	=	5,000	Baht		Construction	=	5,000	Baht
Total cost for storage tank	=	418,800	Baht		Total cost for storage tank	=	392,925	Baht
Gas scrubber	=	6,000,000	Baht		Gas scrubber	=	6,000,000	Baht
Gas Blower	=	375,000	Baht		Gas Blower	=	375,000	Baht
Gas meter	=	405,000	Baht		Gas meter	=	405,000	Baht
Pipe	=	150,000	Baht		Pipe	=	150,000	Baht
Total cost of biogas system	=	7,348,800	Baht		Total cost of biogas syste	=	7,322,925	Baht

Cost of electricity generation system was 40 million baht (grid system was included).

Table A14 Cost of generator

Electricity generator			
Gas engine generator set			
Generator 2 MW with Grid	=	40,000,000	Baht

The maintenance costs of the mesophilic and thermophilic treatment plants were calculated by 4% of investment cost, and 5% of the electricity production system's installation cost. It was calculated following the equation below.

$$\text{Total maintenance costs } \left(\frac{\text{baht}}{\text{year}}\right)$$

$$= 4\% \text{ of installation costs } \left(\frac{\text{baht}}{\text{year}}\right)$$

$$+ 5\% \text{ of electricity production system } \left(\frac{\text{baht}}{\text{year}}\right) \ldots\ldots\ldots\ldots\ldots\ldots.\text{(A10)}$$

The operating cost for mesophilic treatment plant were assumed to be only the employee salary, while the employee salary and heating costs during plant shut down was used for thermophilic treatment plant. Two electric boilers were installed for thermophilic treatment plant during plant shut down (60 days).

Table A15 Operating and maintenance costs

Maintenance cost	=	4	%
Operating cost			
Engineer 2 persons	=	216,000	Baht/year/person
	=	432,000	Baht/year
Operater 15 persons	=	108,000	Baht/year/person
	=	1,620,000	Baht/year
Overall	=	2,052,000	Baht/year

Table A16 Electric boiler installation and operating cost

Electric boiler *2			
Q_{loss}	=	5.46	kW
Waste water circulated	=	0.09	kg/s
Electric boiler	=	10	kW
Electricity consumed	=	240	kWh/day
(60 day in 1 year)	=	14,400	kWh/year
Price of installation	=	100,000	Baht
Price of operating (3.9 baht/unit)	=	56,160	Baht/year

All of the electricity production was sold to the grid, with on adder of 7 year. In adder period the electricity was sold 4.3 baht/kWh. After 7 year, the electricity was sold 4 baht/kWh.

Table A17 Benefits for financial analysis

Benefit			
Electricity sell	=	4	Baht/kWh
TR	=	38,070	kWh/day
(1 year Operated 292 days)	=	11,116,323	kWh/year
	=	43,353,660	Baht/year
Adder (7 years) 0.3 Baht/kWh	=	3,334,897	Baht/year
Overall Benefit	=	46,688,557	Baht/year
MR	=	35,689	kWh/day
	=	10,421,217	kWh/year
	=	40,642,747	Baht/year
Adder (7 years) 0.3 Baht/kWh	=	3,126,365	Baht/year
Overall Benefit	=	43,769,112	Baht/year

Financial analysis

WACC of discount rate calculation was analyzed using Equation A11.

$$\mathrm{WACC} = \mathrm{Kd} * (1 - \text{tax rate})\mathrm{Wd} + \mathrm{KeWe} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathrm{A11})$$

Where:

Kd was cost of debt, which as a bank interest value

tax rate was the rate from the revenue department

Wd and We was the ratio of investment cost of project

Ke was risk of the project. There is 10 – 15 %