THE INFLUENCE OF TEMPERATURE AND TYPES OF FILTER MEDIA ON THE PALM OIL MILL EFFLUENT (POME) TREATMENT USING THE HYBRID UP-FLOW ANAEROBIC SLUDGE BLANKET (HUASB) REACTOR

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CHAPTER 1

INTRODUCTION

1.1 Background on palm oil

The oil palm, *Elaeis guineensis*, is indigenous to West Africa, with the first countries that started to plant the oil palm being Sierra Leone, Liberia, the Ivory Coast, Ghana, and Cameroon (Yusoff, 2006). Palm oil cultivation has gained prominence due to the versatility of the crop. Therefore, the cultivation of the crop has expanded beyond Africa to South East Asia, since the seeds were carried over to Indonesia in 1848. The seeds reached Malaysia in 1871 (Basiron & Chan, 2004).

The tropical ambiance and the rich soil contributed to the success of oil palm plantation in Malaysia. In 1911 and 1912, Malaysia witnessed the first commercial oil palm plantation, the crop began to be regarded as an important economic asset (Tate, 1996). The development of palm oil industry can be divided into three phases; the experimental phase (1895 to 1916), the plantation development phase (1917 to 1960) and the expansion phase that is currently in place. Palm oil cultivation has been significantly advantageous to Malaysia. It has contributed to the economy by being a successful export as well as means of livelihood for about 0.3 million families employed in various land schemes and palm oil lands (Abdeghameed, 2005).

An important development in palm oil cultivation was the increase in planted areas. In 1960, the total planted area was 54,638 hectares. This has rapidly expanded in 40 years to reach 3,376,664 hectares in 2000 (Salmiah, 2000). A rapid increase in crude palm oil products as well as exports in Malaysia occurred in 1979, in order to enhance the national income increase employment opportunities. To boost research and development, the Palm Oil Research Institute of Malaysia (PORIM) was established in 1979 to enable expansion of palm oil cultivation. Subsequently, PORIM merged with the Palm Oil Registration and Licensing Authority (PORLA) in 2000 to form the Malaysia Palm Oil Board (MPOB).

Today, Malaysia is one of the leading producers and exporters of palm oil in the world, contributing to 49.5% of the world's palm oil production and 64.5% of global exports according to the Malaysian Palm Oil Board Survey in 2004.

Figure 1.1: Transportation of fresh fruit bunches

1.2 Palm oil processing

Try Recently, a considerable growth in the palm oil industry has been recorded in Malaysia due to the increase in planted area. Malaysia has become a leading producer and exporter of palm oil in the world, overtaking Nigeria in 1971 (Yusoff, 2006). Palm oil is essentially a national wealth. However, the rapid increase in palm oil plantations has been putting a strain on the environment due to the waste of the oil extracting process as well as the gas emissions from the subsequent treatment of mill effluents. The typical processes for extracting the crude palm oil (CPO) are illustrated in Figure 1.2.

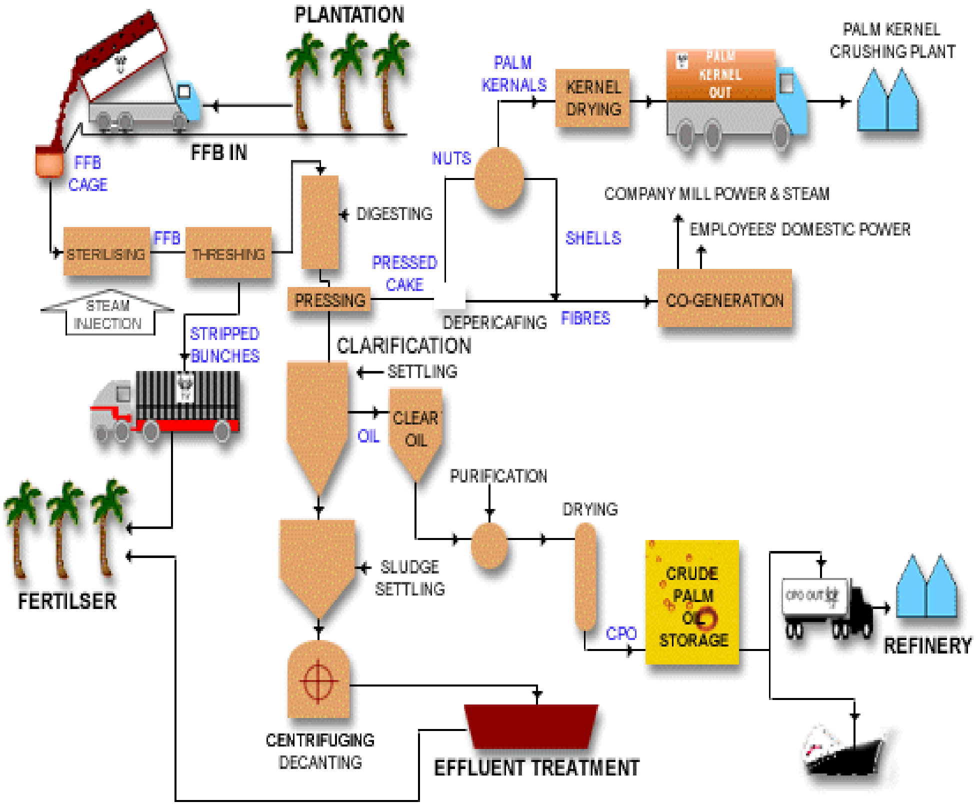

Figure 1.2: Crude palm oil extraction process

The fresh fruit bunches (FFB) are harvested from the palm trees. The bunches are then sent directly to the mill for processing, each FFB consists of hundreds of fruits, each fruit containing a nut surrounded by a bright orange pericarp from which the crude palm oil (CPO) is extracted (Borja & Banks, 1994a). The FFB are sterilised at 3 bar pressure and 140°C for 1.5 hrs in a unit called a steriliser. The aims of sterilising are to prevent free fatty formation and prepare fruit for subsequent processing. The steam, from the steriliser, is one of the fundamental sources of liquid effluent (Chow & Ho, 2000).

After sterilisation, the FFB passes through the bar screen of a stripper (thresher) after which the detached fruits are collected from the FFB. A bucket conveyor is used to transport the fruit to the digester which mashes the fruit by its rotating arms. The heating in this stage plays an essential role in mashing the fruit.

After the digestion process, a twin screw presses the digested mash to extract the CPO under high pressure. In order to enhance the continuous flow of oil, it is necessary to add hot water. Later, the CPO is discharged to the clarification system to purify and separate the oil. After this stage, the nut and fibre are carried to the depericarper for separation. The contents of CPO extracted from the crew presses represent: (35-45%) palm oil, (45-55%) water, in addition to some fibrous materials in varying forms. Through the clarification stage, these materials are pumped for separation and they pass through a very high speed centrifuge and a vacuum drier before disposal to the storage tank (Chow & Ho, 2000).

The final unit is the hydrocyclone which separates the kernels and shells. The discharged wastewater from this unit represents the last form of wastewater and is known as palm oil mill effluent (POME).

1.3 Problem statements

The economical progress in Malaysia owes a large part to the wide growth of palm oil plantations, where Malaysia is now one of the largest producers (11.9 million tonnes annually) for this crop (Idris *et al*., 2010). However, it is estimated that for 1 tonne of CPO produced, 5-7.5 tonnes of water are required, and more than 50% of the water will end up as POME (Ahmad *et al*., 2003). Raw POME is characterised as liquid wastewater, brownish in colour, non toxic, with unpleasant odour, colloidal suspension of 95-96% water, 0.6-0.7% oil and 4-5% total solids (Idris *et al*., 2010), and having a high temperature ranging between (80-90ºC) (Ahmad *et al*., 2003; Yacob *et al*., 2006). Directly discharging a high strength effluent such as POME to the main drainage can cause high environmental damage. In fact, the discharge regulations of POME as well as the exercising of other environmental controls, the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Order, 1977 and the Environment Quality (Prescribed Premises) (Crude Palm Oil) Regulations, 1977, were promulgated under the Environmental Quality Act, 1974 (Ahmad *et al*., 2003). Therefore, it is believed that more efficient treatment is highly required to achieve that demand.

Various high rate anaerobic reactors have been examined for POME treatment in the laboratories including the Anaerobic Filter (AF), the Anaerobic Baffled Reactor (ABR), the Membrane Anaerobic System (MAS), Fluidized Bed Reactor (FBR), Immobilised Cell Reactor (ICR), and the Hybrid Up-flow Anaerobic Sludge Blanket (HUASB) reactor (Poh & Chong, 2009). However, there is still a need to reveal the effect of some operational parameters (temperature and organic loading rate) on the anaerobic treatment process. Therefore, this research using the HUASB reactor attempted at investigating the influence of temperature on the treatment efficiency of the system.

1.4 Objectives

The main objective of this study is to investigate the feasibility of HUASB reactor, packed with OPS filter media material, for the biological treatment of POME. Moreover, the specific objectives are presented as follows:

a) To study the efficiency of HUASB reactor treating POME.

b) To study the effect of using OPS as filter media as compared to fine gravel (FG) material.

c) To study the effect of temperature on treatment efficiency of the whole treatment system.

d) To investigate the development of sludge bed granules as the main agent of wastewater treatment.

1.5 Scope of work

This research involves an extensive laboratory investigation that include study on the feasibility of using OPS as filter packing material, the treatment of wastewater under various temperatures and the examination of sludge development in the reactors. The scopes of this study are as follows:

a) Operation of three laboratory scale HUASB reactors namely, R1, R2 and R3 in order to treat POME for long term operation (233 days).

b) Two types of filter packing materials of OPS and FG were used in the reactors R3 and R2, respectively.

c) A wide range of temperatures (37-61ºC) was applied to R3 to assess the temperature influence on the treatment of POME.

d) The seed sludge used for the microorganisms' growth process was collected from anaerobic pond of palm oil mill treatment units.

e) Raw OPS packing material used was ranging in diameter sizes between 0.8 to 2.6 cm.

f) For assessing the reactor performance, several parameters include pH, chemical oxygen demand (COD), total solids (TS), total suspended solids (TSS), volatile suspended solids (VSS), total nitrogen (TN), total phosphorus (TP), colour and turbidity were monitored during the run of experiment.

g) A series of operational conditions (OLRs and HRTs) were implemented to assess the reactor performance as well as effectiveness.

h) A thorough examination of the material characteristics, the influent and effluent quality and the sludge bed development was conducted to assess the feasibility of POME treatment by the use of HUASB reactors.

1.6 Expected results

The study aims to provide an alternative method of POME primary treatment that may be implemented for a full-scale anaerobic pilot in palm oil plantations in Malaysia while making use of the oil palm shell as an available filter media type.

1.7 Thesis outline

This research is investigating the anaerobic treatment of POME using the HUASB reactor and the effects of temperature and types of filter media on the treatment efficiency. Chapter 1 presents general introduction, including a problem statement, objectives of the study, scope of work, expected results and thesis layout. Chapter 2 presents a general literature review covering the topics of history of anaerobic wastewater treatment, POME properties and treatment technologies, anaerobic filter, UASB technology, HUASB reactor and its implementation, anaerobic sludge granulation, controlling factors for anaerobic reactors and their advantages and disadvantages. Chapter 3 is presenting the used methodology of treating POME using three HUASB reactors with several operational conditions. Chapter 4 is presenting the significant results and discussions of treating POME in terms of material characteristics, reactor performance and sludge bed development. Chapter 5 presents a general conclusion, recommendations and future works. References and appendices are attached at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Anaerobic wastewater treatment

The concept of anaerobic wastewater treatment was initially implemented around one hundred years ago, where the first invention of the septic tank system (Mouras automatic scavenger 7) has been reported by Wang (1994). Several investigations have followed in the past few decades to enhance the anaerobic treatment efficiency and its range of applicability as well (Abbasi *et al*., 2012). However, one of the main problems with using anaerobic systems is the long term start-up operation. That is mainly because of the long hydraulic retention time to prevent sludge wash out. Therefore, the introduction of the anaerobic filter in 1968 was useful in terms of reducing the start-up of the reactor operation by providing attach growth making use of the anaerobic filter support material for bacterial adherence (Alkalay *et al*., 1997).

Recent research conducted by Leita˜o *et al*. (2006) has endeavoured to produce a more efficient reactor for the anaerobic treatment of wastewater, with new technologies being introduced that proved successful in operation and removal. Anaerobic wastewater treatment processes are still the most popular treatment methods especially in tropical countries (van Lier, 2008). It has been implemented for various types of wastes, especially high rate wastewater which is the main composition of industrial wastewater (Lettinga *et al*., 2000). In the Netherlands, more than 2266 full-scale anaerobic treatment units have been successfully operated (van Lier, 2008). Key to this success of anaerobic wastewater treatment is mostly attributed to its low production of sludge as well as its generation of energy in a form of biogas (Leitaˇo *et al*., 2006; van Lier, 2008). Figure 2.1 shows the application of anaerobic system for the treatment of wastewater in Japan.

Figure 2.1: Anaerobic wastewater treatment plant (Takuma, 2005)

The development of the use of anaerobic wastewater treatment was started in the Netherlands in 1978, where the up-flow anaerobic sludge blanket (UASB) system was first used by Dr. Lettinga for treating wastewater in a sugar refinery. Subsequently, it has been implemented in treatment of wastewater in the beverage industry, distilleries, fermentation, food industry and the paper industry. In addition, the use of anaerobic technology has been expanded and comprises of the treatment of chemical and petrochemical industry effluents (Abbasi *et al*., 2012).

The UASB concept is also considered highly suitable for domestic wastewater treatment especially in warm climates in tropical countries. Over the past two decades, the UASB technology has been commonly used, due to its all-round performance for high-low organic content wastewater treatment. The key factor that ensures high performance in anaerobic reactors is the right selection of operational conditions (Schmidt & Ahring, 1996). Therefore, the success of the anaerobic processes totally depends on the operational parameter.

In fact, two main categories of wastewater treatment for the treatment of high strength wastewater like POME are the anaerobic treatment and the aerobic treatment.

Figure 2.2 illustrates the main process of each type. It can be seen that if POME is treated aerobically, an excessive sludge is produced. It can be expected that the sludge produced in the aerobic treatment may contain around half of the initial wastewater due to the fact that POME contains high range of solids of around 11,500-79,000 mg.L^{-1}. This large amount of sludge needs further treatment which establishes the need for anaerobic treatment.

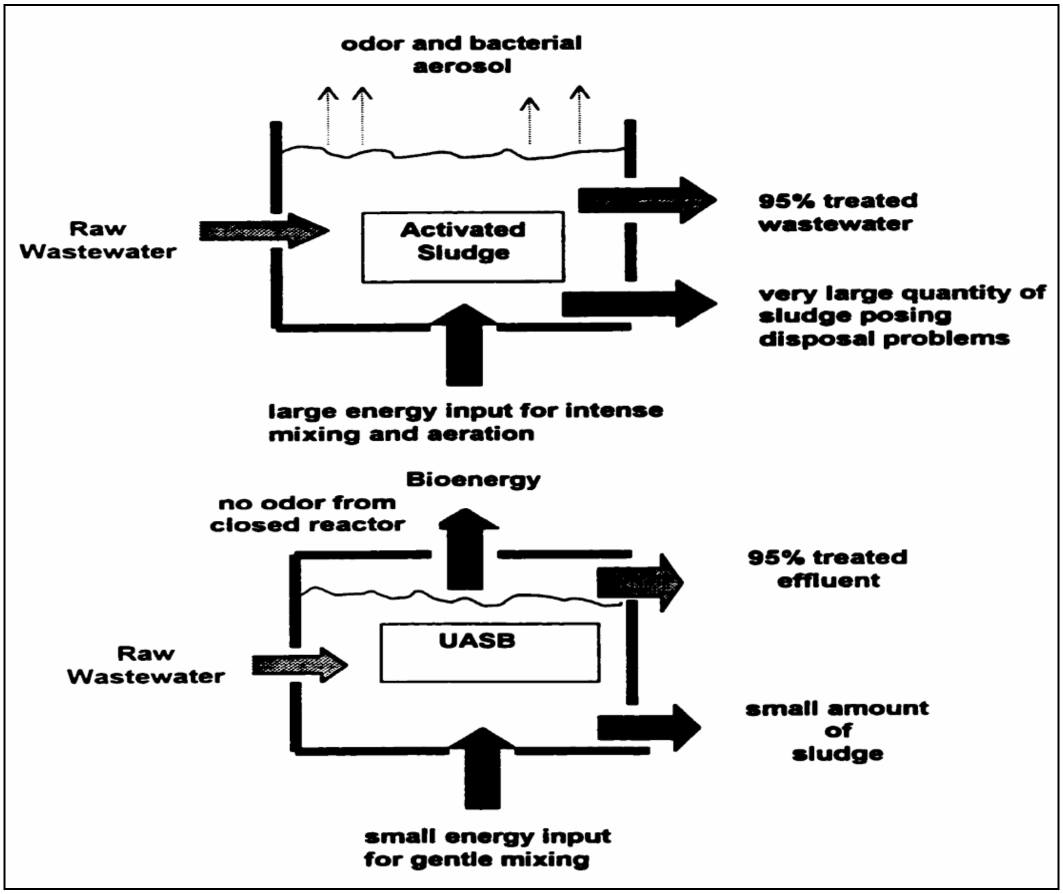

Figure 2.2: The main process description of aerobic and anaerobic treatment of wastewater (Singh, 1999)

2.2 Anaerobic treatment principles and mechanisms

It is believed that such a lack of dissolved oxygen (DO) in wastewater would likely let specific organisms acting to digest organics. Various kinds of organisms anaerobically degrade the complex organics into their simple compounds (Shin *et al.*, 2011). The conversion of very complex organics (carbohydrates, proteins and lipids), can be achieved through four main phases, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis, with each phase acting with specific organisms.

There should be equilibrium of the phases on which organics are broken down into their final products (CH_4 and CO_2). For instance, if acidogenesis outcompetes the other phases, the reactor tends to sour due to the excessive acetic acids produced by the acidogenic organisms (Lettinga *et al.*, 2000). The other phases have a similar tendency, with each phase being complementary to the other. Figure 2.3 illustrates the conversion steps of organics during the anaerobic treatment of wastewater.

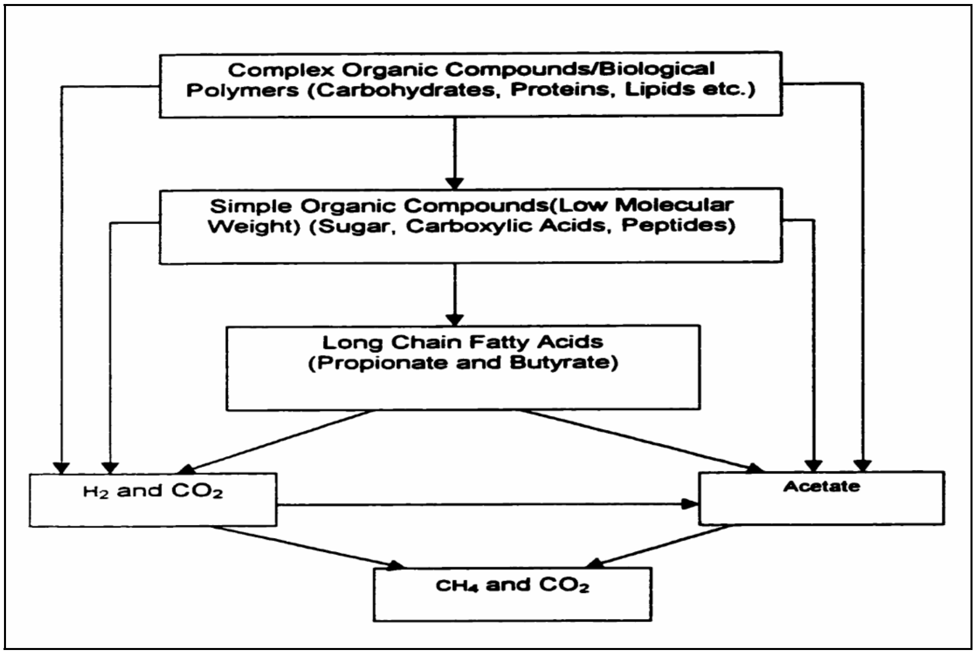

Figure 2.3: The biodegradation of wastewater compounds during the anaerobic process of wastewater treatment (Singh, 1999)

The anaerobic principle varies from the aerobic principle in that it occurs in the absence of DO. Aerobic reactions, in which oxygen act as the electron acceptor, cannot take place in such conditions. The conversion of large complex organics into smaller compounds such as methane is believed to occur according to the following anaerobic overall equation (Equation 2.1) (Krishnan, 2009).

$$\text{Complex organics} \xrightarrow{\text{Organisms activity}} CH^4 + CO^2 + H^2 + NH^3 + H^2S + \text{New bacterial cell} \qquad (2.1)$$

In fact, the process of anaerobic digestion involves many chemical exchanges affected by the physical changes as well as the environmental circumstances (Alimahmoodi, 2004). Nonetheless, Lettinga *et al*. (2000) have specifically divided anaerobic digestion into six separate processes listed below.

a) Hydrolyses of biopolymers such as proteins, carbohydrates and lipids.

b) Fermentation of amino acids and sugars.

c) Anaerobic oxidation of long chain fatty acids and alcohol.

d) Anaerobic oxidation of intermediary products such as volatile acids, except acetate.

e) Conversion of acetate to methane.

f) Conversion of hydrogen to methane.

2.2.1 Hydrolysis

The initial step in the anaerobic process is hydrolysis, which is responsible for the conversion of particulate matter to soluble compounds, which can in turn be hydrolysed further to simple monomers that are used by bacteria to perform fermentation (Yan *et al*., 2011). This step is essential to allow the organics to pass through the bacterial cell walls to be used as energy for adequate metabolisms (Krishnan, 2009). Moreover, it has been defined as the first order process and the rate limiting step, on which the degradable soluble COD will be available (Graaff *et al*., 2010). This could be achieved by the excrement of extra-cellular and hydrolytic enzymes. Hydrolysis step involves the biodegradation of carbohydrates, proteins and lipids into simpler compounds like fatty acids, amino acids and sugars. It is suggested that COD removal does not occur during the hydrolysis of organics (Maier *et al*., 2000).

2.2.2 Acidogenesis

The second step in anaerobic biodegradation is known as acidogenesis, which involves the conversion of the complex organic matter that has been hydrolysed (including long chain organic acids, sugars and amino acids) to CO_2, H_2, NH_3, carbon acids and alcohol. The organic substances serve the function of both electron acceptors and donators. The main category of bacteria that contribute in this phase is the acidogens, which include a wide variety of organisms. This phase of the anaerobic biodegradation could be mediated by facultative and/or obligate bacteria. Previous studies have reported that the obligate anaerobes form the larger portion of the acidogenic bacteria as compared to the facultative anaerobes (Maier *et al*., 2000). In this phase, COD removal may depend on the conversion of soluble organics to biomass and to gases in the form of carbon dioxide (CO_2) and hydrogen (H_2) (Krishnan, 2009).

2.2.3 Acetogeneses

This phase can be considered an extension of acidogenesis. It involves the oxidation of the rest of the long chain fatty acids (propionate and butyrate) which are not converted in the acidogeneses phase. Additionally, several carbon atom acids are degraded to acetate, whereas odd number carbon acids are degraded to acetate and hydrogen ion (H^+). In this phase, there is no organic stabilisation but only a change in the form of the organics (Krishnan, 2009). The main products of this phase are the acetic acid, CO_2 and H_2.

2.2.4 Methanogeneses

The third phase in the anaerobic biodegradation of wastewater is methanogenesis. This phase is responsible for the conversion of the last product of acetate and H_2 to biogas. There are two main categories of methanogens (methanogesis organisms) that are responsible for this, namely *aceticlastic* methanogens and hydrogen utilising methanogens. The *aceticlastic* methanogens are responsible for splitting the acetate into methane and carbon dioxide as in the following reaction (Equation 2.2) (Metcalf & Eddy, 2003).

$$CH^3COOH \xrightarrow{\text{Acetotrophic}} CH^4 + \text{New bacterial cell} \qquad \Delta G^\circ = -32\ \text{kJ} \qquad (2.2)$$

The hydrogen utilising methanogens use the hydrogen as electron donor and carbon dioxide as the electron acceptor for the process of methane production. Methane fermentation can be considered a crucial sub process in the anaerobic biodegradation of wastewater. In this phase, the stabilisation of organics can be attributed to the conversion of acetic acid to methane. Generally, about 72% of methane produced in an anaerobic process is from acetate formation (Metcalf & Eddy, 2003). The rest 28% is contributed by the reduction of carbon dioxide using hydrogen as the energy source by carbon dioxide reducing bacteria as shown in Equation 2.3 (Krishnan, 2009).

$$CO^{2} + 4H^{2} \xrightarrow{\text{Hydrogenotrophic}} CH^{4} + CO^{2} + 2H^{2}O + \text{New bacterial cell} \qquad \Delta G^{\circ} = -138.9\ \text{kJ} \qquad (2.3)$$

2.3 POME properties

The palm oil mill effluent (POME) has a high organic content of more than 50,000 mg/L chemical oxygen demand (COD) (Hassan *et al*., 2004). Generally, the raw POME is liquid, brownish in colour, non toxic, has unpleasant odour, colloidal suspension, and has high temperature ranging between (80-90) ºC. It consists of 95%-96% water, 0.6-0.7% oil, and 4%-5% solids including suspended and volatile solids (Borja & Banks, 1994a).

The palm oil mill approximately discharges 1.5 tonnes of wastewater as a result of processing 1 tonne of FFB (Ahmad *et al*., 2003). This amount of wastewater is generated from the three palm oil production processes, i.e., steriliser condensate, separator sludge (clarification wastewater) and hydrocyclone wastewater.

The three processes vary in waste disposal, with the steriliser effluent mostly containing a significant amount of organic content in the form of chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The clarification sludge contains the highest level of solids and unrecovered oil and grease compared to the other processes. The hydrocyclone effluent consists of a considerable amount of degradable organic matter (Hassan *et al*., 2004). Each of these processes generates the POME (Table 2.1).

The characteristics of raw POME vary due to the operation and quality control of individual mills (Basiron & Chan, 2004)**.** Treatability of POME has been examined with a wide range of technologies and approaches. Owing to its properties, POME can be easily treated using a biological approach. Due to its high organic and mineral content, POME may be considered a suitable feeder for the sludge bed microorganisms.

Table 2.1: Characteristics of POME and its respective standard discharge limit by DOE (Ahmad *et al*., 2003)

General parameters	Concentration	Standard limit
PH	4.7	5-9
Oil & grease	4,000	50
Biochemical oxygen demand (BOD_3)	25,000	100
Chemical oxygen demand (COD)	50,000	-
Total solids (TS)	40,500	-
Suspended solids (SS)	18,000	400
Total Nitrogen (TN)	750	150

Note: all the parameter units are measured in mg/L except PH

2.4 POME treatment technologies

Due to its high organic and mineral content, Lettinga *et al*. (2000) reported that the excessive amount of organic materials in wastewater can be treated successfully by using biological treatment methods. Previous studies have verified the vital role of microorganisms in digesting the high organic materials (Vijayaraghavan *et al*., 2007). Generally, the suitable method for POME treatment is anaerobic treatment due to the low nutrient content in POME to be aerobically treated. However, this small amount of nutrient has been considered more than sufficient for the anaerobic biodegradation process (Irvan *et al*., 2012). Nonetheless, various methods including the aerobic process have been employed in POME treatment.

2.5 Anaerobic filter (AF)

Anaerobic reactors such as anaerobic filter reactors depend on the natural tendency of mixed microbial populations that can even attach and accumulate at the surface of filter elements (support materials). Microorganisms that adhere to the support material surfaces grow, reproduce and produce extracellular polymeric (ECP) substances that normally extend from the cells themselves, forming the gelatinous matrix called a biofilm. It has been reported that bacterial attachment is mediated by polymeric material, primarily polysaccharide, which extends from the cell to form a tangled mass of fibres, termed a glycocalyx. The accumulation and persistence of a bio-film is the net result of several physical and biological processes that occur simultaneously, although their relative rates change through the various stages. In the anaerobic filter reactor, the packing is fixed and the wastewater flows up through the interstitial spaces between the packing and bio-growth. While the first anaerobic filter processes were packed with rock, a variety of designs employing synthetic plastic packing are being used currently. A large portion of the biomass responsible for treatment in the up-flow attached growth anaerobic processes is loosely held in the packing void spaces and not just attached to the packing material (Metcalf & Eddy, 2003). The anaerobic filter is filled out with support materials arranged in sheet, ring, sphere or random configurations which provide the best conditions for microbial attachment in the form of biofilm. The reactor may be operated in up-flow or down-flow mode (Bodĭk *et al*., 2000). In an up-flow filter, the packing bed is fully submerged. The down-flow can work either submerged or non-submerged. The up-flow anaerobic filter is basically a contact unit, in which wastewater passes through a mass of biological solids contained inside the reactor by a support medium (Krishnan, 2009). The biomass of the anaerobic filter reactor can be as the following:

a) Biomass attached to the support media's surface.

b) Biomass entrapped within the media matrix.

c) Biomass held as a granulated or flocculated sludge mass underneath the media.

Regarding the start-up of anaerobic reactors, it has been indicated that more time is consumed for best start-up, and disturbances are more than in aerobic reactors (Ramakrishnan & Gupta, 2006). The start-up of the anaerobic filter is still considered a major area of research. Many researchers have reported long start-up periods of 2-3 months to 1 year (or even more) for the anaerobic reactors. Accordingly, it has been reported that long duration of start-up period is a major drawback of the anaerobic wastewater treatment systems. Therefore, considerable efforts have been made to study the granulation process but the mechanisms involved in the formation of sludge granules are still unknown. A better understanding of the factors affecting biomass aggregation and adhesion, the two main mechanisms of biomass retention, could make the start-up more efficient and rapid. Table 2.2 shows some studies that have been performed using the anaerobic filter reactors.

Table 2.2: Previous studies conducted on the anaerobic filter (Poh & Chong, 2009)

Wastewater	Operating OLR kg.m^{-3}. day^{-1}	COD removal (%)	Methane composition (%)	Reference
Slaughterhouse wastewater	1.0–6.5	79.9	51.1	(Ruiz *et al*., 1997)
POME	1.2–11.4	94.0	63.0	(Borja & Banks, 1994b)
Baker's yeast factory effluent	1.8–10.0	69.0	65.0	(van der Merwe & Britz, 1993)
Distillery wastewaters	0.42–3.4	91.0	63.0	(Russo *et al*., 1985)
Landfill leachate	0.76–7.63	90.8	-	(Wang & Banks, 2007)

2.5.1 Support materials role in AF

The main purpose of packing the anaerobic filters with support materials is to retain solids inside the reactor, either by the biofilm formation on the surface of the support materials or by the retention of solids in the interstices of the medium or below it. Specifically, the purposes of the packing media can be listed as follows (Krishnan, 2009):

a) Acting as a device to separate solids from liquid.

b) Helping to promote a uniform flow in the reactor.

c) Improving the contact between the components of the influent wastewater and the biological solids contained in the reactor.

d) Allowing the accumulation of high amount of biomass, with a consequently increased solids retention time.

e) Acting as a physical barrier to prevent solids from being washed out from the treatment system.

Various types of materials have been used as packing media in biological reactors including quartz, ceramic blocks, oysters and mussel shells, limestone, plastic rings, hollow cylinders, PVC modular blocks, granite, polyethylene balls and bamboo. The packing media have been designed to occupy considerable volume of the reactor to reach approximately 50 to 70% of the total volume of the reactor. Today, there are different types of plastic packing media available in the market, ranging from corrugated rings to corrugated plate blocks. The specific surface areas of these plastic materials usually range from 100 to 200 $m^2.m^{-3}$ (Krishnan, 2009). Some types of packing media are more efficient than others in the retention of biomass. The final choice depends on the specific local conditions, economic considerations and operational factors.

The requirements for good packing media of anaerobic filter are: a) the large surface area on which high biomass is attached at the surface of the support materials; b) high porosity and therefore larger area for more bacterial interior accumulation; c) rough surface on which bacterial attachment to the surface of support materials is easier, and; d) easy to make the full-scale application of the system feasible. Elmitwalli *et al*. (2000) indicated that specific surface area, porosity, surface roughness, pore size and orientation of the packing material are important factors influencing the anaerobic filter reactor performance. High surface area and porosity, large pore size and rough surface area for packing material would mostly improve the performance of an AF reactor.

2.5.2 Development of AF

As mentioned previously, the introduction of anaerobic filter (AF) dates back to the late 1960s, with a growing application since that time for treatment of both domestic wastewater and a diversity of industrial effluents. Two important developments in the application of anaerobic processes are the development of the anaerobic contact process and the development of the anaerobic filter (Krishnan, 2009). The key concept of both processes relates to the ability to control mean cell retention time (MCRT) independently of hydraulic retention time. This feature permits anaerobic treatment at lower temperatures. Moreover, it has been stated that without increasing MCRT independently of hydraulic retention time, very large reactor volumes are required, making anaerobic treatment techniques tricky. Since heating is not required in tropical climates, low strength wastes, which produce only small quantities of gas per unit volume of waste treated, can be effectively treated by the anaerobic filter or anaerobic contact process.

In addition to the initial studies, the anaerobic filter has been used to treat different types of wastewater by numerous researchers and has been particularly popular for treating high strength industrial wastewater. Fang & Chui (1994b) used the hybrid reactor which is the combination of the anaerobic filter (AF) and the up-flow anaerobic sludge blanket reactor (UASB), they have indicated treatment performance enhancement and better treated effluent quality.

2.6 Up-flow anaerobic sludge blanket (UASB) reactor

The successful operation of the UASB reactor is based on the selective ambient and conditions for better development of microbial communities in the sludge region of the reactor, to obtain high digestion for wastewater which normally contains organic materials. Many factors affect microbial growth including the feed pH, organic loading rate (OLR), reactor temperature, hydraulic retention time (HRT) and the wastewater concentration and content. The UASB process was developed by Dr. Gatze Lettinga in the late 1970's at the Wageningen University (The Netherlands). The UASB reactor is mainly classified under biological reactors due to its biological nature of treatment. Recently, biological treatment has obtained special attention by researchers due to its sustainability (Madhubabu *et al*., 2007). The UASB reactor is characterised by its low energy demand, simple construction and high removal efficiency (Show *et al*., 2004; Arthur & Glover, 2012). The UASB reactor has been shown to treat high rate as well as low rate wastewater with various kinds of pollutants. A survey by Ganesh *et al*. (2007) investigated the greatest usage of the UASB reactor. More than 108 studies indicate the relative proportion of work between 1999 and 2004 as illustrated in Figure 2.4.

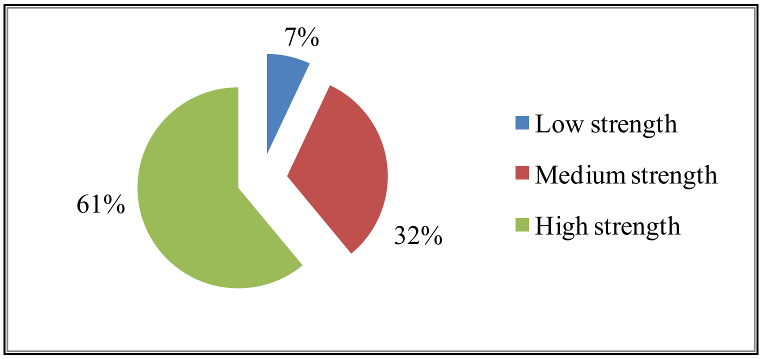

Figure 2.4: Relative proportion of work done during 1999-2004 on the treatment of industrial wastewaters of different strengths by UASB reactors (Ganesh *et al*., 2007).

The main factors influencing the reactor performance are: the granulation development in the sludge bed, the wastewater characteristics, the effect of the nutrients and other environmental factors. The granulation process plays a vital role in the wastewater treatment process and is especially important (Fang *et al*., 1994a). Various anaerobic pure bacteria have been used to successfully conduct the degradation processes in the bioreactor. The schematic diagram of the UASB reactor is illustrated in Figure 2.5.

The UASB reactor was designed to treat high strength wastewater as well as the low strength one with considerable savings in material, energy, and equipment maintenance. The UASB reactor is characterised by its high removal efficiency. Nonetheless, the main disadvantage of this system is represented in the long start-up interval of reactor for complete acclimatisation.

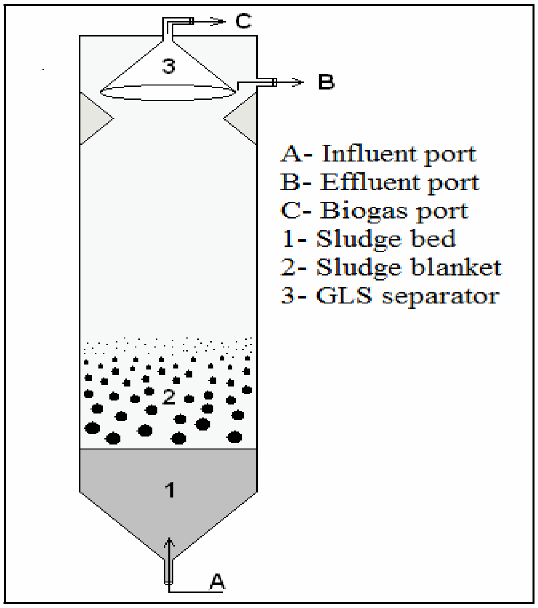

Figure 2.5: Schematic diagram of UASB reactor (Schmidt & Ahring, 1996)

2.6.1 UASB set-up

The up-flow anaerobic system mainly consists of a tank, pump, and gas- liquid-solid (GLS) separator equipment. It is necessary to provide a suitable ambient for the treatment which is essential to obtain a high digestion for wastewater. The UASB system has been used in tropical countries due to its high performance in warm ambience (Leita˜o, 2004). Various volumes have been designed while generally implementing the same concepts of passing the wastewater upwards through the sludge bed where the microorganisms are present in order to digest the wastewater substrates. The UASB reactor is designed to treat high strength wastewater which is the main composition of industrial wastewater, in addition to its capability of treating municipal wastewater. The GLS separator was previously designed at the top of the reactor as illustrated in Figure 2.6-(a). The main reasons to provide UASB system with GLS were: a) to collect the discharged biogas properly; b) to reduce the biomass washout by entrapping particles in sludge blanket; c) flocculating or settling the particles; d) to decrease the turbulence which results from gas rising in the form of bubbles; and e) to reduce the solid content in the effluent. The separation process is fundamental to the success of anaerobic digestion (Figure 2.6-b).

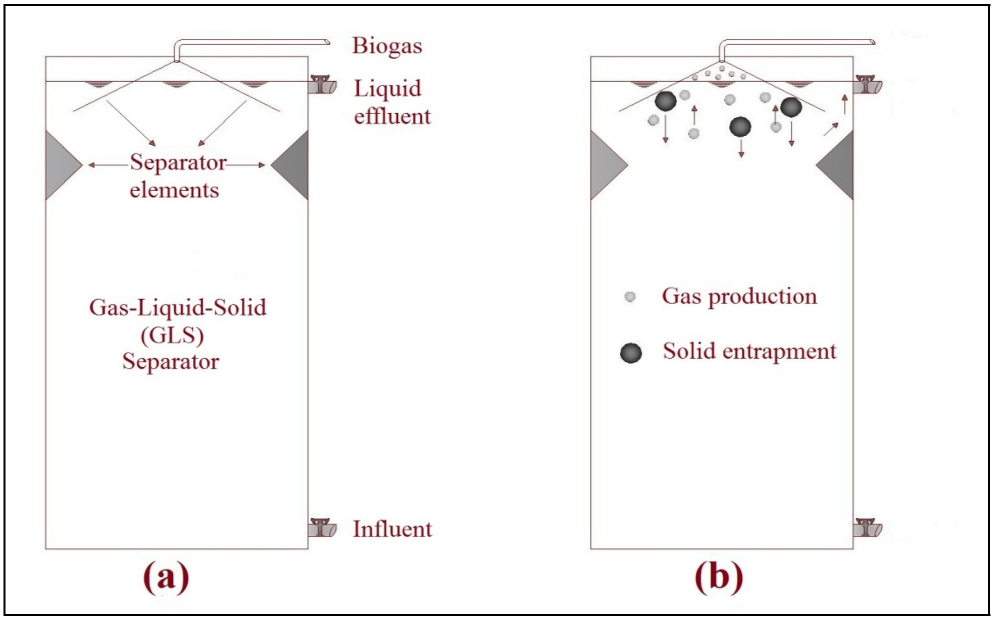

Figure 2.6: (a) GLS Design, (b) GLS Process

2.6.2 UASB start-up and operation

Start-up should be performed according to operating conditions which include pH of influent, HRT, OLR, initial sludge amount, suitable temperature of treatment, and the up-flow velocity (UV). van Haandel *et al*. (2006) suggested a range for the operating conditions which are mentioned in Table 2.3.

Table 2.3: Parameters suggested for first operation (van Haandel *et al*., 2006)

Parameter	Unit	Value
PH	-	6.3-7.8
Hydraulic retention time (HRT)	hr	4-20
Organic loading rate (OLR)	kg COD. m^{-3}. day^{-1}	0.4-3.6
Sludge charge	-	(10-30)%
Temperature	°C	20-55
Up-flow velocity (UV)	$m.hr^{-1}$	0.2-1

The start-up period continues until it reaches steady-state operation, which is recognised by its stability (stable operation), with the changes in removal efficiency being below 10%. The duration to reach steady-state ranges around 3-8 weeks and totally depends on the operational variables. Controlling the system is necessary to monitor COD in and out.

2.6.3 UASB improvement and evolution

Previously, the understanding of the UASB reactor was limited to its treatment of high rate organic wastewater. But various researchers have demonstrated the feasibility of the UASB reactor to treat municipal wastewater. Tiwari (2005) tested the low rate wastewater and under the low loading rate of 1.48 kg COD.m^{-3}.d^{-1}, showed a high removal efficiency of 95%. However, in order to expand and develop the application of the UASB reactor, new ideas have been studied and practically implemented. It has also been recommended to adding natural ionic acids for treating very strong wastewater in order to enhance the digestion process by providing support material. This was implemented by Leal *et al*. (2006) who treated oil and grease of dairy plantation effluents by using hydrolytic enzyme as a removal assistant factor for the oil and grease. A good COD removal efficiency of 90% was recorded. It has been indicated that adding a filter to the UASB system accelerated the process and enhanced the digestion of reactor. This modification is called Hybrid Up-flow Anaerobic Sludge Blanket (HUASB). Yu *et al.* (2000) reported in attempting to enhance and increase the sludge granules size in UASB reactor, the possibilities of adding natural or artificial materials in order to obtain much larger granules. Enhancement and development of UASB reactor has been done in order to expand the use of the reactor.

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