Treatment of Anaerobically Digested Palm Oil Mill Wastewater using Sequencing Batch Reactor (SBR)

by

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LIST OF ABBREVIATIONS

	Description
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DOE	Department of Environment
DO	Dissolved Oxygen
EGSB	Expanded Granular Sludge Bed
F/M	Food to Microorganism ratio
HRT	Hydraulic Retention Time
MLSS	Mixed-Liquor Suspended Solid
MLVSS	Mixed-Liquor Volatile Suspended Solid
MPOC	Malaysia Palm Oil Counsel
OLR	Organic Loading Rate
OUR	Oxygen Utilization Rate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
POM	Palm Oil Mill
SBR	Sequencing Batch Reactor
SOUR	Specific Oxygen Uptake Rate
$SOUR_{max}$	Maximum Specific Oxygen Uptake Rate
SVI	Sludge Volume Index
TSS	Total Suspended Solid
TN	Total Nitrogen
UASB	Upflow Anaerobic Sludge Blanket
UFF	Upflow Fixed Film
UNEP	United Nations Environment Programme
Y_{VSS}	Yield calculated based on Volatile Suspended Solid Content
Y_{TSS}	Yield calculated based on Total Suspended Solid Content

LIST OF SYMBOLS

Symbol	Description	Unit
b_D	Decay coefficient	d^{-1}
$COD_{effluent}$	COD of effluent waste	mg/L
$COD_{influent}$	COD of influent feed	mg/L
$\frac{dx}{dt}$	Biomass growth rate = μ	d^{-1}
f_D	Fraction of active biomass contributing to biomass debris	-
K_s	Substrate half saturation constant (substrate concentration at half μ_{max})	mg/L
OUR	Oxygen utilization rate	mg/L·h
OUR_D	Oxygen uptake rate due to biomass decay	mg/L·h
OUR_{total}	Overall oxygen uptake rate	mg/L·h
q_x	Specific substrate utilization rate	mg/L·h
S	Substrate concentration	mg/L
S_f	Final COD concentration	mg/L
S_i	Initial COD concentration	mg/L
ΔS	Net change of COD concentration	mg/L
μ_{max}	Specific maximum growth rate	d^{-1}
$\mu_{\mathrm{max,H}}$	Specific maximum growth rate of heterotrophic biomass	d^{-1}
μ_x	Specific growth rate	d^{-1}
V_{sludge}	Volume of sludge layer of 1L mix liquor after settling time of 30 min	ml
X	Biomass concentration	mg/L
X_H	Concentration of heterotrophic biomass in reactor	mg/L
$X_{H,t}$	MLVSS concentration at t time	mg/L
$X_{H,0}$	Initial reactor MLVSS concentration	mg/L
X_f	Final biomass concentration	mg/L
X_i	Initial biomass concentration	mg/L
ΔX	Net change of biomass concentration	mg/L
Y	Yield coefficient	-

RAWATAN AIR SISA KILANG KELAPA SAWIT
YANG TELAH MELALUI PENCERNAAN ANAEROBIK
DENGAN MENGGUNAKAN REAKTOR BERKELOMPOK BERJUJUK

ABSTRAK

Di Malaysia, rawatan biologi air sisa kilang kelapa sawit diamalkan secara luas sebelum pelepasan air sisa tersebut ke sumber-sumber air yang lain. Walaupun terdapat banyak kajian mengenai rawatan secara anaerobik, namun begitu kajian mengenai rawatan secara aerobik masih tidak cukup. Dalam kajian ini, reaktor berkelompok berjujuk (SBR) telah digunakan untuk memperkayakan biojisim aerobik dalam rawatan air sisa kilang kelapa sawit secara aerobik. SBR tersebut mempunyai isipadu kerja sebanyak 8 L dan nisbah pertukaran 25%. Kepekatan influen air sisa kilang kelapa sawit berbeza dari lingkungan 5000 ± 500 mg COD/L hingga 11500 ± 500 mg COD/L. Kandungan oksigen terlarut (DO) dikawal dalam lingkungan 4.0 hingga 5.5 mg/L, manakala pH tidak dikawal. Prestasi SBR diperhatikan pada kadar muatan organik (OLR) dan masa tahan hidraulik (HRT) yang berlainan. Ia ditemui bahawa hampir 90% daripada kandungan COD dalam sisa air kilang kelapa sawit telah berjaya disingkirkan tanpa bergantung pada OLR dan HRT. 10 % COD yang tertinggal dalam efluen mencadangkan bahawa air sisa kilang kelapa sawit mengandungi 10 % COD yang tidak boleh diuraikan atau sukar diuraikan dalam tempoh HRT 5 hari. Didapati bahawa penggunaan oksigen ketika influen COD tidak berkurang mungkin disebabkab oleh pengoksidaan produk simpanan dalam biojisim. Selain itu, diketahui bahawa peningkatan OLR akan meningkatkan kepekatan biojisim yang mana menyebabkan formasi biojisim kecil dan bersuraian yang berupaya mendap rendah. Di samping itu, penilaian kinetik pertumbuhan telah dilakukan terhadap biojisim aerobik. Dalam kajian ini, penilaian kinetik pertumbuhan melibatkan biojisim yang merawat air sisa POM (lebih kurang 5000 mgCOD/L) secara aerobik dalam SBR (beroperasi pada 28 ºC, tanpa mengawal pH) dijalankan dengan menggunakan model Monod dan data eksperimen. Pekali pereputan (b_D) and kadar penghasilan biojisim (Y) yang didapati adalah 0.132 day^{-1} and 0.424 mg biojisim/mgCOD terguna. Di samping itu, kadar pertumbuhan tentu maksimum (μ_{max}) yang didapati adalah 2.4 day^{-1} manakala pekali separuh tepu (K_s) berkenaan pada COD adalah 0.429 g COD/L. Keputusan menunjukan rawatan aerobik menggunakan SBR berpotensi tinggi untuk meningkatan prestasi sistem rawatan air sisa kilang kelapa sawit.

Kata kunci: rawatan biologi, reaktor berkelompok berjujuk, air sisa kilang kelapa sawit, model Monod, kinetic pertumbuhan

TREATMENT OF ANAEROBICALLY DIGESTED PALM OIL MILL (POM) WASTEWATER IN SEQUENCING BATCH REACTOR

ABSTRACT

In Malaysia, biological treatment which consist of series of anaerobic and aerobic ponds is being widely used to treat palm oil mill wastewater. Although there are many researches regarding the anaerobic system of the biological treatment but the studies of aerobic treatment is still scarce. An aerobic treatment is used to further reduce the chemical oxygen demand (COD) content of the anaerobically treated POM wastewater in order to meet the discharge requirement. In this study, sequencing batch reactor (SBR) was used to enrich biomass for the biological treatment of the aerobically treated POM wastewater. The SBR has a working volume of 8 L and an exchange ratio of 25%. The influent concentration of the POM wastewater was varied from 5000 ± 500 mg COD/L to 11500 ± 500 mg COD/L. The dissolved oxygen (DO) was controlled in the range of 4.0 to 5.5 mg/L, whereas the pH was not controlled. The performance of the reactor was monitored at different organic loading rates (OLR) and hydraulic retention time (HRT). It was found that around 90 % of the COD content of the POM wastewater has been successfully removed regardless of the OLR and HRT applied to the SBR. The remaining 10% of the COD in the effluent suggests that the POM wastewater contains around 10 % of non-biodegradable or slowly biodegradable COD which cannot be degraded by the biomass within the HRT of 5 days. It was found that the oxygen uptake near the end of each treatment cycle might due to oxidation of storage product by the biomass. Further, it is revealed that the increase of OLR increases the biomass concentration which results in the formation of small dispersed biomass with reduced settleability. Apart from that, the growth kinetic of the aerobic biomass was evaluated. In this study the growth kinetics of the biomass involved in the aerobic treatment of POM wastewater (around 5000 mgCOD/L) in SBR (operating at 28 ºC, without controlling pH) were determined using Monod model and experimental data. The decay coefficient (b_D) and biomass yield (Y) were found to be 0.132 day^{-1} and 0.424 mg biomass/mg COD consumed respectively. On the other hand, the maximum specific growth rate (μ_{max}) was estimated to be 2.4 day^{-1} while the half saturation constant (K_s) with respect to COD was determined to be 0.429 g COD/L. The result shows that the aerobic treatment using SBR has high potential to enhance the conventional treatment system of POM wastewater.

Keywords: biological treatment, sequencing batch reactor, palm oil mill wastewater, Monod model, growth kinetic

CHAPTER 1
INTRODUCTION

1.1 Introduction to Palm Oil Mill Wastewater in Malaysia

Malaysia accounts for around 39% of world palm oil production and about 44% of the world's total exports of palm oil (MPOC, 2013) (MPOC, 2013). The cultivation of oil palm increased at a fast pace in early 1960s under the government’s agricultural diversification programme. Today, 4.49 million hectares of land in Malaysia is under oil palm cultivation; producing 17.73 million tonnes of palm oil and 2.13 tonnes of palm kernel oil (MPOC, 2013).

Although palm oil production has brought much profit to the country and have a huge contribution towards economic growth, the rapid development has also creates environmental pollution issue due to the significant amount of waste products produced from the oil extraction processes. These wastes consist of fibrous material (such as empty fruit branch, palm press fiber and palm kernel shell) and less fibrous material (such as palm kernel cake and liquid discharge). Generally all the wastes except wastewater will be reused as boiler’s fuel or fertilizer. Palm oil mill (POM) wastewater consists of high biological oxygen demand (BOD), chemical oxygen demand (COD), oil and grease, total solids and suspended solid (DOE, 1999). If the untreated POM wastewater is discharged into receiving water bodies it is certain to cause considerable environmental problem such as eutrophication and clean water scarcity.

Thus, Malaysian Environmental Quality Act 1974 and Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations (1977) were enforced by the government where the effluent from POMs must comply with the discharge limit set in these regulations (Maizatun & Mustafa, 2011). Therefore, the discharge from the palm oil mill requires efficient management system in order to utilize, treat and dispose with the aim of the environmental conservation and reducing deterioration of air and river quality.

Most of the treatment methods of POM wastewater are based on 3 major principles which are biological treatment, physical-chemical treatment and advance treatment. Dated back to the early 1980s, biological treatment has been used for the treatment of POM wastewater treatment; systems such as tank digestion with facultative ponds and tank digestion with mechanical aeration are commonly used (Ma & Ong, 1985). The implementation of other types of reactors (such as upflow anaerobic sludge blanket reactor and upflow fixed-film reactor) for biological treatment of POM wastewater have also been studied (Borja & Banks, 1994). However, it was inevitable that the open ponding methods were generating other problems such as the disposal of bulking sludge and the emission of greenhouse gases.

As time proceeds, researchers were seeking possibilities of other kinds of treatments in which the stability and efficiency were emphasized. Physical-chemical methods such as membrane separation, adsorption and coagulation-flocculation treatment were tested and achieved some promising results (Karim & Hie, 1987; Ahmad et al., 2003a; Vijayaraghavan et al., 2006; Zhang et al., 2008; Ahmad et al., 2009). Although the treatment using these methods achieve the discharge standard set by Department of Environment of Malaysia, unfortunately they also encounter some drawbacks. The use of the materials such as membranes, adsorbent, coagulant and flocculant in physical-chemical treatment includes high costing especially in the regeneration of the materials. Therefore, it is economically impractical to imply them in industrial scale. Likewise, researchers have tried to treat POM wastewater using advance oxidation process such as hydrogen peroxide photolysis and the method has stalled in doubt of economically viable.

1.2 Problem Statement

Many studies have been successfully carried out to improve the treatment of POM wastewater, yet the palm oil industry still facing limitation to widely implement the outcome to the investigations (Ahmad et al., 2003a). Therefore, the biological treatment using conventional open pond system with lower cost is preferred. The conventional biological pond treatment system requires a large land area for the treatment of large discharge volume of POM wastewater. Furthermore the operation of the open-pond system will lead to the emission of odor gas, pollute the clean water sources and create an ideal scenario for the spreading of tropical diseases such as dengue and malaria. As a result, the palm oil mills always failed to consistently meet the discharge regulation set by the Department of Environment (DOE, 1999). The improper treatment of POM wastewater has affected the clean water sources and disturbs the ecosystem surrounding the water sources.

Therefore, the economical, sociological as well as the ecological issues have to be well considered when planning for the treatment system of POM wastewater. The use of open-pond system in biological treatment has to be modified for a proper utilization of land usage, where the sequencing batch reactor (SBR) was introduced. Recently, the SBR is proven to be successful in treating different types of wastewater. It was estimated that the size of land usage when using the SBR can be reduced to 20% of the land used by open-pond system (de Bruin et al., 2004). It has been reported that SBR has the potential to be integrated to the biological treatment of POM wastewater (Chan et al., 2010; Gobi et al., 2011; Chan et al., 2012a). Based on the studies, SBR can achieved high COD removal rate treating POM wastewater. However, the application of SBR in the POM wastewater treatment is still limited because of the high suspended solid content in the wastewater which might lead to treatment failure. In order to integrate the SBR into the POM wastewater treatment system, it was proposed that the SBR should be coupled with another treatment unit (Chan et al., 2012a). The unit coupled with the SBR should be able to reduce the suspended solid content which will flow to the SBR. Generally there are several anaerobic ponds, facultative ponds and aerobic ponds in conventional biological wastewater treatment system of POM wastewater, by coupling the SBR to the downstream of anaerobic pond, it might save up the land area used by the facultative and aerobic ponds. Further, the application of SBR also reduces the emission of odor and eliminates the possibility for spreading diseases (Appleford et al., 2004).

Apart from that, conventional biological pond system tends to have a poor separation between the treated effluents and the biomass (Liu et al., 2003). The flush out of biomass from the treatment system will reduce the treatment efficiency and affect the eco-system of the effluent receiving water sources. The operation of SBR helps the separation of biomass from treated effluent. It was reported that the biomass treating POM wastewater in SBR was able to achieve good settling performance. This characteristic helps to retain the biomass in the reactor while discharge the effluent with lesser suspended solid (Gobi et al., 2011). However the detailed study on the characteristics of biomass treating POM wastewater in SBR is yet to be undertaken. Studies on the suitability of SBR and the behavior of the biomass in treating POM wastewater need to be carried out before applying this technology in industrial scale. Therefore, in this study, the characteristic and growth kinetic behavior of the biomass involved in the aerobic treatment of POM wastewater using SBR was investigated.

1.3 Objective

The aim of this research is to gain further insight on the characteristics of biomass treating POM wastewater. The specific objectives of the study are;

1) To study the effect of organic loading rate and hydraulic retention time on the performance of sequencing batch reactor treating palm oil mill wastewater;
2) To investigate the organic carbon removal and oxygen uptake rate by biomass in sequencing batch reactor treating palm oil mill wastewater;
3) To evaluate the growth kinetics of the biomass involved in the aerobic treatment of palm oil mill wastewater in sequencing batch reactor.

1.4 Scope of Study

The scope of this study consists of two major parts, namely; characterization of biomass treating POM wastewater and the evaluation of growth kinetics of biomass in POM wastewater using SBR. Before performing characterization, the biomass was enriched in a SBR. During the enrichment, continuous monitoring of COD removal efficiency and the changes of biomass concentration in SBR treating POM wastewater were conducted. At the same time, cycle study was performed in order to observe the COD concentration and the oxygen uptake rate (OUR) changes throughout a typical treatment cycle. The next part of the characterization study was to investigate the effect of organic loading rate (OLR) and hydraulic retention time (HRT) on COD removal.

Meanwhile, the evaluation of growth kinetics of biomass in POM wastewater was carried out using Monod model. First, the decay coefficient, b_D was estimated using batch test method. Then batch experiments at various organic loading were conducted to obtain the yield, Y of the biomass. Later, the determination of half saturation constant, K_s and maximum growth rate, μ_{max} were carried out using respirometer. The kinetic parameter obtained can provide an insight on the characteristics and activities of the biomass involved in the aerobic treatment of POM wastewater in SBR.

1.5 Organization of Thesis

This thesis consists of five main chapters. In the Introduction chapter (Chapter 1), background regarding the conventional methods for POM wastewater treatment in Malaysia was briefly introduced. Besides, the reason of doing this research was emphasized in the problem statement. In addition, the objectives and the scope of study are explained in this chapter. Furthermore, a clear view on the arrangement of the thesis was summarized here.

Meanwhile, technical information related to this study was thoroughly discussed in Literature Review (Chapter 2). More information about the POM wastewater, POM wastewater treatment system, the use of SBR in wastewater treatment and the microbial growth kinetic are listed in this chapter. In the Methodology (Chapter 3); equipment, steps of data collection, analyzing procedure and mathematical equations were shown accurately.

The Results and Discussion section (Chapter 4) compiled the experimental data and the interpretations of the data. Data obtained from the characterization of biomass and the evaluations of growth kinetics are presented in this chapter. The experimental results were elaborated and discussed.

Lastly, the Conclusion (Chapter 5) finalized and concluded the research achievements based on the discussion in Chapter 4. Based on the outcome, recommendations were given to the future works as to enhance the POM wastewater treatment system as well as improving the methods of experimental conduct.

CHAPTER 2
LITERATURE REVIEW

2.1 Palm Oil Mill (POM) wastewater

2.1.1 The origins of POM wastewater

Huge amount of wastewater is generated during the processing of the fresh fruit bunch to produce palm oil. Figure 2.1 shows a simple schematic diagram of a typical palm oil mill's extraction process. The main sources of the wastewater from the extraction process are (i) Hot water or steam used for the sterilization process, (ii) Hydrocyclone of separation of broken shell from kernels and (iii) Water used for clarification process.

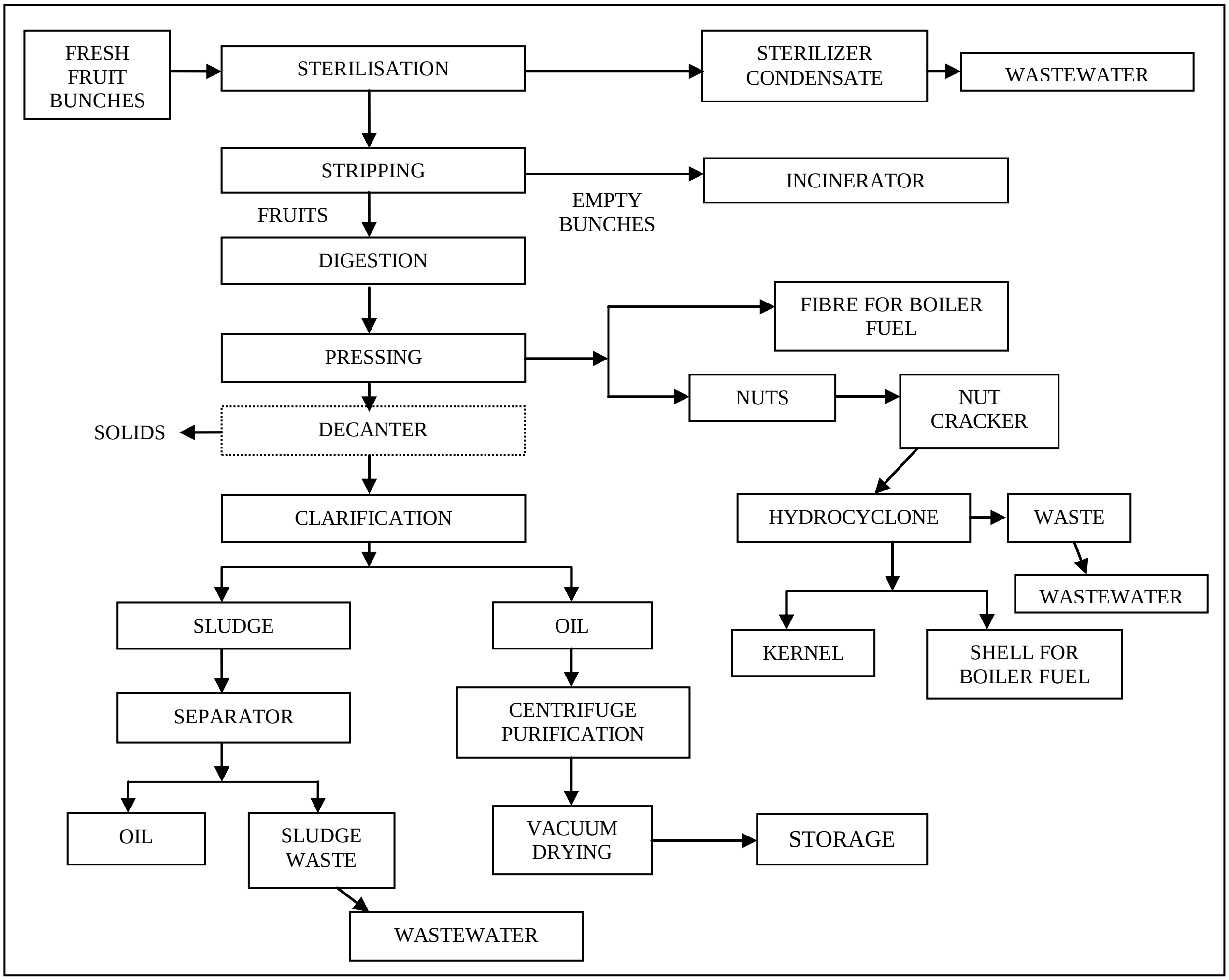

Figure 2.1: Palm oil extraction process (Ma & Ong, 1985)

A tonne of crude palm oil production needs about 5 to 7 tonnes of water, and more than 50% of this amount will be discharged as wastewater (Ahmad et al., 2003a). The wastewater collected from palm oil processing will be treated before discharged to the other water sources. Generally, the methods used to treat POM wastewater can be categorized as physio-chemical and biological methods. In Malaysia, palm oil mills prefer to utilize the biological treatment to treat POM wastewater (MPOB, 2013).

2.1.2 The Characteristic of POM wastewater

Table 2.1 shows the general characteristic of POM wastewater and its discharge limit propose by the Malaysian government. The nitrogen available in POM wastewater will act as the nutrient for the growth of algae which could later cause eutrophication. The high COD and BOD in the wastewater consume the dissolved oxygen and create anaerobic condition in the receiving water bodies. Furthermore, POM wastewater without treatment has a low pH and at a temperature around 50 ~ 60 ˚C. Therefore, proper POM wastewater treatment system is needed in order to ensure the treated discharge meets the regulation limits.

Table 2.1: Characteristic of POM wastewater and the discharge limit propose by government (DOE, 1999)

	General POM WASTEWATER		DOE Standards
Parameter*	Range	Mean	
BOD	10250 – 43750	25000	100
COD	15000 – 100000	51000	- **
TSS	5000 – 54000	18000	400
pH	3.4 – 5.2	4.2	5.0 ~ 9.0
TN	180 – 1400	750	200

* All parameter in mg/L except pH

** DOE Malaysia does not specify the discharge COD value for POM wastewater

2.2 Treatment technologies of POM wastewater

2.2.1 Biological treatment of raw POM wastewater

Various effluent treatment schemes have been proposed and used to achieve the discharge standard set by the government. Generally the POM wastewater treatment methods can be categorized into i) the physio-chemical method and ii) the biological method. In physio-chemical method, the POM wastewater is treated using physical processes such as membrane separation process (particle size), clarification using coupled filtration with aeration (particle size and weight), and evaporation technology (boiling point of POM wastewater) (UNEP, 1994; Ahmad et al., 2003a; Ahmad et al., 2003b). Meanwhile the biological treatment usually consists of several steps before discharging the effluent into the receiving water bodies. Normally it involves the reduction of wastewater strength using biomass; following by the sedimentation of biomass, where the supernatant (treated effluent) is discharged while biomass is retained and be removed during maintenance process.

Although there are many investigations on physical treatment showing positive results in treating POM wastewater, but the researches are limited to laboratory scale. Further research is still needed for the full scale application and implementation for industrial purposes. Moreover, the application of physical treatment for POM wastewater is limited due to the high cost of the equipment and the mechanical energy consumption involved in the treatment. Thus, in Malaysia, more than 85% of POM wastewater treatment is focusing on biological treatment. Generally biological treatment consists of an anaerobic facultative pond system followed by an open tank digester coupled with extended aeration in the pond to further reduce the amount of BOD and COD (Ma et al., 1982; Poh & Chong, 2009).

The anaerobic pond possesses several drawbacks such as requirement of large land area, effectiveness of sludge settling ability, the sensitivity of biomass due to temperature and pH changes and the emission of unpleasant odor. Further, the biological treatment pond for POM wastewater possesses high hydraulic retention time (HRT) of around 20 to 200 days (Chan & Chooi, 1984). By considering the amount of POM wastewater generated during the period, a very large volume of land is needed to contain the wastewater during the treatment period. Moreover, at the aerobic pond the biomass needs oxygen in order to degrade the organic contents in POM wastewater, therefore the depth of the pond needs to be shallow enough for the oxygen to penetrate to the bottom of the pond in order to ensure effective treatment efficiency. Thus, the overall area needs to be increased to compensate the lost of depth to retain the wastewater (Henze et al., 2008). Due to the large size and configuration of ponds, it was difficult to control and maintain the efficiency of the treatment process. The treatment efficiency of biomass is highly dependent on the treatment pH, temperature and dissolved oxygen (DO) concentration, the failure to control these parameters could lead to the failure of the wastewater treatment system (Henze et al., 2008).

Therefore, researchers shift to find solution by trying to treat POM wastewater using bioreactors. The primarily idea is to focus on reducing the total land area needed for treatment, maintaining more reliable control and consistent treatment. Borja and Banks (1994) have shown that upflow anaerobic sludge blanket reactor (UASB) manage to achieve a COD removal of 96 % in treating POM wastewater. In addition, the total land area used has drastically reduced while also shorten the HRT (Borja & Banks, 1994). As continuation of the research on UASB, the sludge blanket in the bioreactor was replaced with a filtration unit. By doing this, the reactor manage to achieve COD removal of around 90% while maintaining at stable operating pH condition (Borja & Banks, 1994). Further, the upflow anaerobic filter system can capture harmful gases (methane and hydrogen sulfide) produce during the anaerobic biological treatment. However, it was found that the UASB reactor has limitation in treating POM wastewater with high suspended solid content at high organic loading rate. Thus, UASB was integrated with upflow fixed film (UFF) to overcome this issue (Najafpour et al., 2006). The UFF layer of the integrated reactor functions to help the detainment of solid inside the reactor. Thus, improved the separation of solid (biomass), liquid (treated effluent) and gas (methane and hydrogen sulfide).

Apart from the UASB, Vijayaraghavan et al. (2007) have monitored the treatment of POM wastewater using activated sludge reactor. They reported a COD removal of more than 95% at HRT of 60 hr. It was claimed that the COD removal percentage could be further increased by the extension of HRT (Vijayaraghavan et al., 2007). Meanwhile, sequencing batch reactor (SBR) has also gained attention from researchers for POM wastewater treatment due to its proven performance in treating both domestic and other industrial wastewater (Liu et al., 2004).

2.2.2 Biological treatment of anaerobically treated POM wastewater

It was known that wastewater treatment with only anaerobic treatment could not remove all the COD content in POM wastewater (Chan et al., 2009). Due to the limitation of anaerobic treatment, the remaining COD within the anaerobically treated POM wastewater has to be further polished in order to meet the discharge standard set by Malaysian government.

Several works have reported positive results of COD removal using SBR in treating wastewater which has similar strength as POM wastewater (Kushwaha et al.; Lo & Liao, 1986, 1989; Uzal et al., 2003; Sirianuntapiboon et al., 2005; Göblös et al., 2008). These works utilize combination of anaerobic-aerobic system in biological wastewater treatment. It is noticed that the works which integrated SBR as the aerobic compartment manage to achieve more than 85 % COD removal.

Further, investigations upon the aerobic treatment of anaerobically treated POM wastewater has been carried out (Zhang et al., 2008; Chan et al., 2010). In particular, Zhang (2008) used EGSB as the anaerobic compartment and an aerobic biofilm reactor as the aerobic compartment in the anaerobic-aerobic biological treatment system. The OLR of the treatment is about 10 000 mg COD/L·day, the result shows that this system manage to achieve total COD removal of 95.6 % (Zhang et al., 2008).

Meanwhile, Chan (2010) studied the biological treatment of anaerobically digested POM wastewater using a lab-scale SBR. The system has feed of about 4200 mg COD/L·day, and it successfully remove about 95 % of the COD content in the feed. The biomass formed in the system shows a good settling properties as it has an average SVI of 65. It was also reported that the system manage to maintain a stable effluent quality which comply with the discharge limit (Chan et al., 2010).

The integration of SBR into biological wastewater treatment system is a promising technology in order to ensure the quality of POM wastewater to meet the discharge standard. Although this technology has been frequently used for treating both industrial and domestic wastewater, but the application for treating POM wastewater is still in its infancy. It has many advantages over other methods and plausible to treat wastewater with similar strength to POM wastewater. Therefore, it is wise to investigate the characteristics and growth kinetics of the biomass enriched in SBR to promote the full-scale implementation of SBR in POM wastewater treatment plant.

2.2.3 Sequencing Batch Reactor

SBRs are used all over the world and have been around since the 1920s. It has been successfully used to treat both municipal and industrial wastewater, particularly in areas characterized by low or varying flow patterns (Mahvi et al., 2004).

Basically, the SBR system operates on a fill and draw basis. The SBR is filled during a discrete period of time and then operated as a batch reactor (Wisaam et al., 2007). After the desired treatment, the mixed liquor is allowed to settle and the clarified supernatant is then drawn from the reactor. The operational cycle of a typical SBR is divided into five discrete time periods: Fill, React, Settle, Draw and Idle as shown in Figure 2.2.

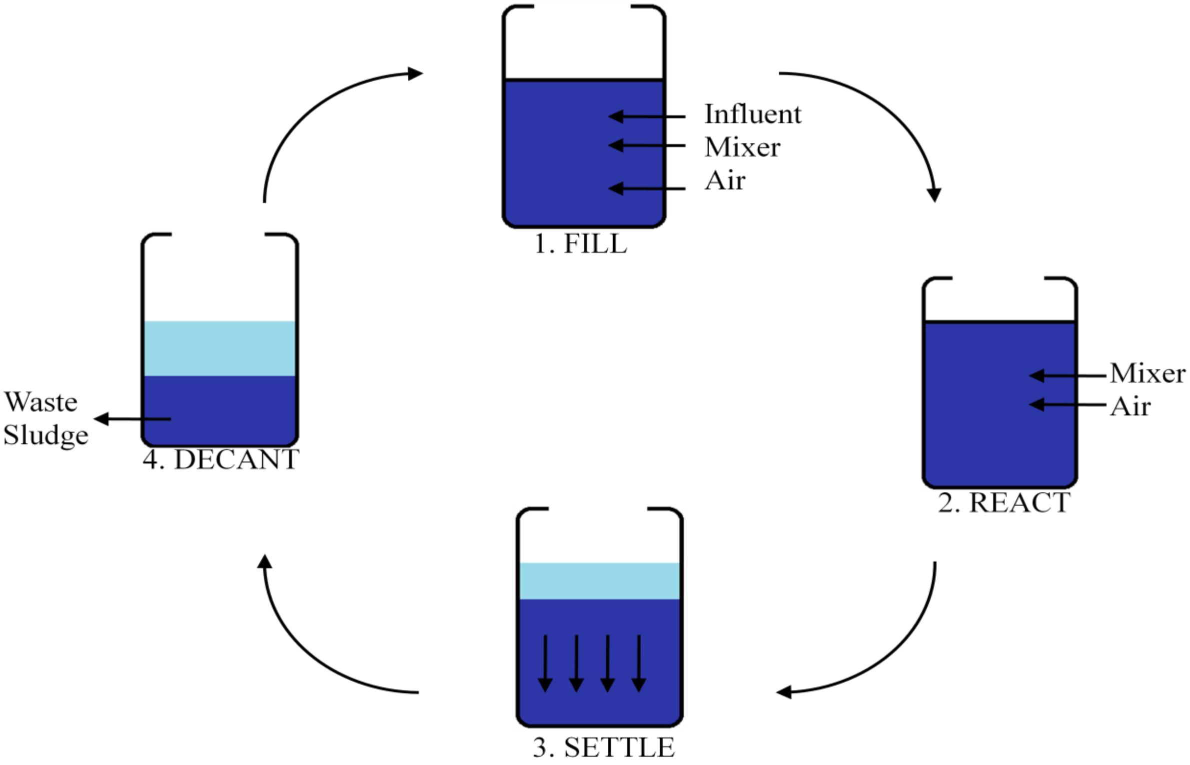

Figure 2.2: Schematic of SBR operation

The main focus of the SBR design is the use of a single tank for multiple aspects of wastewater treatment. An SBR operates in a true batch mode with aeration and sludge settlement both occurring in the same tank.

Table 2.2: Description of SBR operational steps

Operational Step	Description
Fill	Addition of substrate into SBR. The added substrate is mixed homogeneously with or without aeration.
React	Input substrate is consumed/degraded by biomass under controlled operating condition.
Settle	Separation of biomass (solid) from treated mix liquor. Biomass is allowed to settle to bottom of SBR while the liquid supernatant will discharge from SBR in following step as SBR effluent.
Decant	Discharge of clarified supernatant from SBR.

The major differences between SBR and conventional continuous flow activated sludge system is that the SBR tank carries out the functions of equalization aeration and sedimentation in a time sequence rather than in the conventional space sequence of continuous-flow systems. A part of that, we can design the SBR system to treat a wide range of influent volumes whereas the continuous system is based upon a fixed influent flow rate. Thus, higher degree of flexibility associated with working in a time rather than in a space sequence can be achieved.

There are many advantages of SBR compared to the continuous-flow systems (Wisaam et al., 2007). SBR does not require secondary settling tanks and sludge return system. Therefore, it can reduce the recurrent cost and lower the capital investment of POM wastewater treatment plant. Comparatively SBR is much smaller and has lower space requirement than the conventional biological wastewater treatment system whereas the saved space can be use for better purpose. In terms of operational reliability, the SBR is also rather easy-to-handle since the homogeneity of the mix liquor in the reactor is easier to control due to the smaller size of SBR. Further, the operational settings of SBR can be regulated to favor the growth of biomass with better settleability. This can improve the separation of biomass from the treated effluent and thus, improve the discharge effluent quality. In a number of situations the application of an SBR system will thus result in lower investment as well as operational costs.

However, the most important factor in determining the success of a biological wastewater treatment system is the ability to maintain the optimal condition for biomass growth within the system itself. In order to optimize the operation or to scale-up the treatment plant, we need to understand and study more about the characteristics of the biomass in treating POM wastewater.

2.3 Microorganisms in biological wastewater treatment

In general, the aim of biological wastewater treatment is to reduce the concentration of organic and inorganic compound in wastewater. In many cases, the biological wastewater treatment is also able to remove nutrients that are capable to stimulate growth of aquatic plants, particularly the removal of nitrogen and phosphorus from agricultural wastewater. Sometimes the biological wastewater treatment also capable to remove the non-settleable colloidal solid and stabilize the organic matter in wastewater (Grady et al., 2011).

During the biological treatment of wastewater, microorganisms are used to convert the carbonaceous organic matter into various gases and new cell membranes (Hung et al., 2012). However, the new cell membranes will also contribute to biological oxygen demand (BOD);

therefore after conversion, the cell membranes has to be separated from the mix solution to complete the wastewater treatment process (Bitton, 2011).

In the other hand, microorganisms must have energy source, carbon source for cellular material and some inorganic nutrients (such as nitrogen, phosphorus, potassium) in order to function properly and being able to reproduce. Hence, the type of microorganisms that presence in biological wastewater treatment plant could be classified according to the energy source and carbon source. As shown in Table 2.3, microorganisms which can construct new cell membranes from inorganic carbon dioxide are known as autotrophic. Meanwhile, microorganisms which use organic carbon as building materials for cell membranes are known as heterotrophic. Meanwhile, for organisms which obtains energy for cell synthesis from sunlight, they are known as phototrophs; if the organisms obtains energy from chemicals reaction, they are known as chemotrophs (Bitton, 2011).

Table 2.3 Classifications of microorganisms by energy and carbon source

Classification	Carbon source	Energy source
Heterotrophic:		
Chemoheterotrophic	Organic carbon	Organic oxidation-reduction
Photoheterotrophic	Organic carbon	Light
Autotrophic:		
Chemoautotrophic	Inorganic carbon	Inorganic oxidation-reduction
Photoautotrophic	Inorganic carbon	Light

When the external substrates are not used to build new cell membranes, biomass will store the excess energy gain as storage products. In condition where the external substrates are always abundant and excess, the growth of biomass and storage of energy can occurs simultaneously. Usually, these storage products exist in form of glycogen, lipids or PHAs (PHB is a type of PHA) (Salehizadeh & Van Loosdrecht, 2004). During the period when the external substrates is depleted (famine period), the storage products are used as the carbon and energy source in order to maintain the biomass cell activities (Willey et al., 2009; Bitton, 2011). Hence, the accumulated storage products will be degraded to enable the biomass to survive the famine period.

2.3.1 Microbial growth

In biological wastewater treatment, microorganisms are the tools that being used to treat wastewater, therefore, the population of microorganisms (biomass) in the treatment system is one of the determining factors for the treatment efficiency. Hence, it is important to understand the nature of microbial growth in order to estimate the microbial population in the wastewater treatment system.

The microbial growth could be described in two terms; namely, microbial growth in term of number and microbial growth in term of mass (Grady et al., 2011). Since the microorganisms multiply exponentially, the number of microorganisms could be described in the form of log natural. Figure 2.3 shows a typical graph of the changes of the number of microbes versus time. In a large biological wastewater treatment plant, it is a tough job to describe and predict the microbial population in terms of numbers using mathematical model. Therefore, it is wise to quantify the microbial population in term of mass. Table 2.4 describes the general phases of microbial growth in term of mass. It should be noted that under normal growth condition, the growth of the microorganisms could be maintained in the presence of excess substrates. Further, there is also possibility that the biomass growth is maintained by consuming the nutrients leftover from the dead cells, even if the provided substrates depletes. By understanding how microorganisms growth in terms of mass, this information is helpful in grasping the concepts for modeling the changes of biomass in a biological wastewater treatment system (Grady et al., 2011).

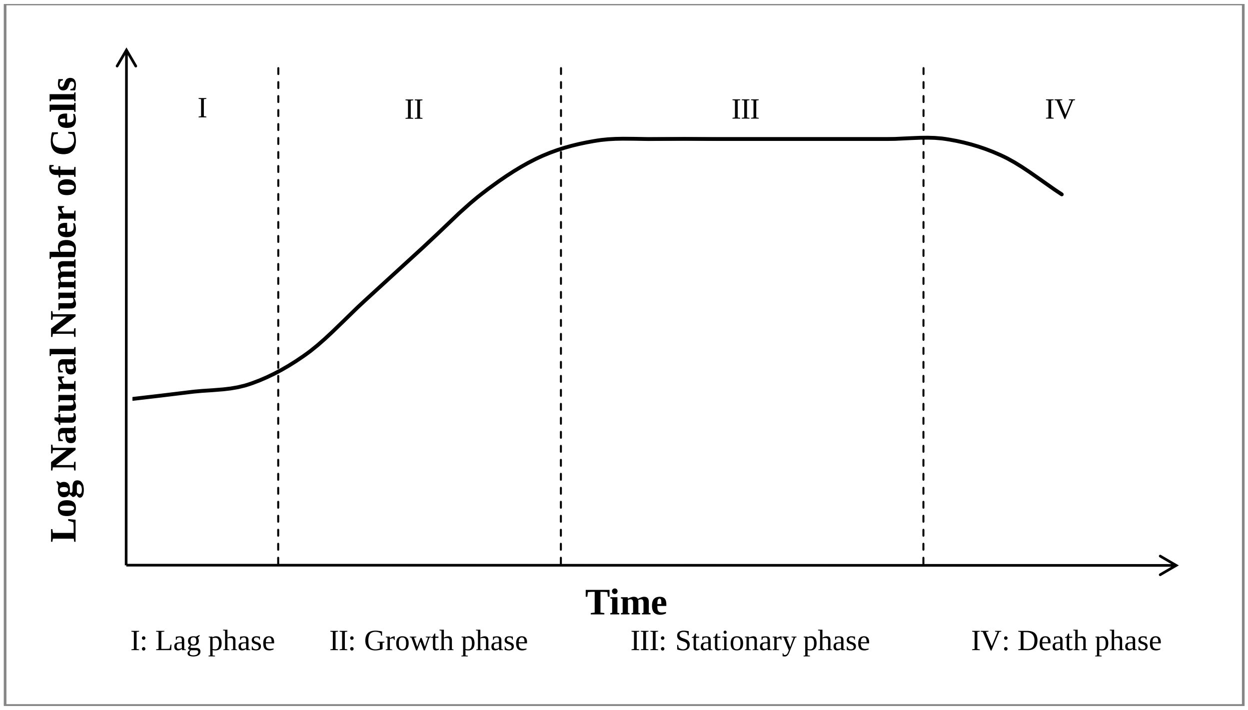

Figure 2.3: Typical microbial growth curve (in term of number)

Table 2.4: Description of phases in typical microbial growth curve (in term of mass)

Phases	Description
Lag phase	The microbes use time to acclimate to the changes on the environment and starts increasing the mass while utilizing surrounding substrates.
Growth phase	In the presents of excess substrates, the microorganisms manage to stockpile energy within cell and reproduce at a constant rate.
Stationary phase	The rate of biomass increment is reduced due to substrates limitation. The mass of biomass maintain at certain value until reaching the next phase.
Death phase	The microbes are forces to metabolized the stored energy because the presence of substrate is minimum. Some microbes might death and undergo lysis, where the cells breaks and the nutrients from the dead cells can be used by the other living cells. this phenomena is known as "cryptic growth".

The growth yield (Y) of biomass is defined as the amount of biomass formed per unit of substrate removed when all energy expenditure is for synthesis. In this context, the substrate is usually taken to be the electron donor, although it can be defined differently. If the electron donor is an organic compound, it is common in environmental engineering practice to express Y in terms of the amount of soluble COD removed from the wastewater. This is because wastewater contains undefined, heterogeneous mixtures of organic compound and the COD is an easily determined measurement of their quantities. Regardless of the nature of the electron donor, it has been a common practice to express the amount of biomass formed on a dry weight basis (i.e., mass of total suspended solids, TSS) or on the basis of the dry weight of ash free organic matter (i.e., mass of volatile suspended solids, VSS). When grown on a soluble substrate, microorganisms have an ash content of about 15% and $Y_{VSS}<Y_{TSS}$. Thus, yields are sometimes expressed as the amount of biomass COD formed per unit of substrate COD removed from the medium. In engineering practices, it remains more convenient to represent yield on a TSS or VSS basis (Hoover & Porges, 1952).

2.3.2 Microbial growth kinetic

Researchers across the globe have been studying on the microbial growth kinetics of microorganism treating wastewater. Generally, the main aim of the investigations is to find various mathematical expressions on the correlation between the growth rates of microorganisms and the substrate utilization in order to describe the possible behavior of the microorganism in a wastewater treatment system. Such mathematical model can be very useful for engineers to design high efficiency wastewater treatment system without failure (Okpokwasili & Nweke, 2006).

One of the most widely used models is the Monod model originally proposed by Jacques Monod in year 1942. The Monod model implies the idea of a growth limiting substrate, the equation is stated as below:

$$\frac{dx}{dt} = \mu_{max} X \frac{S}{K_s + S} \tag{2.1}$$

where $\frac{dx}{dt}$ = biomass growth rate = μ,

μ_{max} = maximum specific growth rate,

X = biomass concentration,

S = substrate concentration,

K_s = Substrate saturation constant (substrate concentration at half μ_{max})

Based on the equation above, we can rearrange the equation into a simpler form where we introduce the specific growth rate, μ_x which is the growth rate per unit mass of the reactor's biomass.

$$\mu_x = \mu_{max} \frac{S}{K_s + S} \tag{2.2}$$

Furthermore, the growth rate in Monod model can be related to yield coefficient and the specific rate of substrate utilization using following equations:

$$Y = \frac{dX}{dS} \tag{2.3}$$

$$\mu_x = \frac{Y}{X} \cdot \frac{dS}{dt} \cong Y \cdot q_x \tag{2.4}$$

Where Y = yield coefficient,

X = Biomass concentration,

q_x = specific substrate utilization rate

On the other hand, Grady proposed a mathematical expression to describe the utilization of oxygen by the microorganism (Grady et al., 2011). Generally the total utilization of oxygen consists of the portion used for microbial growth and the portion used for the microbial endogenous process and it can be described as:

$$OUR = \left(\frac{1-Y}{Y}\right) \cdot \mu_x \cdot X + (1 - f_D) \cdot b_D \cdot X \qquad (2.5)$$

where OUR = oxygen utilization rate,

Y = yield coefficient,

X = biomass concentration,

f_D = fraction of active biomass contributing to biomass debris,

b_D = decay coefficient,

μ_x = specific growth rate.

As time proceeds, other derivatives of the Monod kinetic model have been implemented to describe the kinetic behavior of biomass in biological treatment of different types of wastewater. As to date, reported model have included the anaerobic biological treatment, aerobic biological treatment, treatment of high organic loading rate and many more (Borja et al., 1995; Zinatizadeh et al., 2006). Therefore the understanding of the growth kinetic characteristics of microorganism involved in the treatment of POM wastewater is considerably important in order to enhance the treatment efficiency.

2.3.3 Biomass in biological treatment of POM wastewater

The biological treatment of POM wastewater includes the anaerobic treatment and aerobic treatment. The major different between these methods is the availability of oxygen presence in the treatment processes. Since most of the microorganisms can only prosper in either aerobic or anaerobic condition, the microbial population in these treatment systems might differ from one to another. Generally, the aerobic treatment process with suitable DO level can prevent the formation of filamentous growth and bulking sludge in the treatment system (Ma & Ong, 1985; Agamuthu, 1995). Further, the oxygen input for the growth of aerobic microorganism is needed for a fast degradation of COD content in POM wastewater. This is a faster and time efficient process with lower HRT than the anaerobic approach (Wu et al., 2010).

However, aerobic treatment process is an energy intensive process, therefore, researchers are giving more attention towards the application of the anaerobic treatment process. For instance the anaerobic system is simple method to construct and has low maintenance cost (Wu et al., 2010). The biomass in anaerobic treatment is a mixed culture system. The biomass consists a majority of microbes, which converts alkenes into acids through fermentation (e.g. yeasts) and microbes, which converts acids into methane gas through methanogenesis (e.g. Methanogen, *Methanosaeta concilii*) (Tabatabaei et al., 2009).

In order to optimize the performance of the anaerobic treatment system, kinetics studies on the biomass in anaerobic treatment of POM wastewater have been carried out. Table 2.5 shows the value of growth kinetics for POM wastewater treatment from various works. The kinetics characterizations were conducted in different types of reactors and treatment systems. Setiadi (1996) has performed the characterization of anaerobic biomass in an anaerobic baffled reactor (Setiadi et al., 1996). The result shows that the biomass has specific maximum growth rate, μ_{max} of 0.20 day^{-1} and half saturation constant, K_s of 0.34 g COD/L at OLR of around 10850 mg COD/L·day. Further, Faisal & Unno (2001) had performed the kinetic analysis on a modified anaerobic baffled reactor (Faisal & Unno, 2001). The result is similar to that of previous reported value (μ_{max} of 0.304 day^{-1}, K_s of 0.313 g COD/L at OLR of around 5330 mg COD/L·day). Meanwhile, the biological kinetics evaluation was carried out on a real anaerobic stabilization pond treatment of POM wastewater (Wong et al., 2009). It shows that the value of K_s is slightly lower but the value of μ_{max} is higher than the value using anaerobic baffled reactor (μ_{max} of 0.524 day^{-1}, K_s of 0.203 g COD/L at OLR of around 3180 mg COD/L·day). The growth kinetics of biomass in an integrated anaerobic-aerobic bioreactor (IAAB) treating POM wastewater at thermophilic condition was evaluated (Chan et al., 2012b, 2012a). The evaluation has been conducted at both the anaerobic and aerobic systems of the reactor using Monod model and Grau second order model. The research reported relatively low value of μ_{max} but high K_s in both aerobic and anaerobic systems (anaerobic system: μ_{max} of 0.125 day^{-1}, K_s of 5.067 g COD/L at 55 ºC and OLR of 19250 ± 8750 mg COD/L·day; aerobic system: μ_{max} of 0.122 day^{-1}, K_s of 3.618 g COD/L at 55 ºC and OLR of 4200 ± 3600 mg COD/L·day) compared to the previous researches.

Table 2.5: Values of μ_{max} and K_S for POM wastewater treatment from various works

Reference	**Type of Treatment**	**OLR, mgCOD/L·day**	**μ_{max}, day^{-1}**	**K_S, g COD/L**
Setiadi et al., 1996	anaerobic baffled reactor	10850	0.20	0.34
Faisal et al., 2001	modified anaerobic baffled reactor	5330	0.30	0.31
Wong et al., 2009	real anaerobic stabilization pond treatment	3180	0.524	0.20
Chan et al., 2012	integrated anaerobic-aerobic bioreactor (IAAB) at thermophilic condition	19250	0.125	5.06

There are still some comparisons between the use of single and mixed cultures in POM wastewater treatment (Karim & Kamil, 1989; Bhumibhamon et al., 2002; Oswal et al., 2002). Normally, the diversity of microorganisms, which exists in anaerobic biological treatment of POM wastewater can also be found in the aerobic treatment system, but in different microbial population. It was found out that the use of single culture (such as *Acinetobacter* sp., *Bacillus* sp. and *Pseudomonas* sp.) can perform better in treating the oil and grease content in POM wastewater (Bhumibhamon et al., 2002). An investigation suggested that Monod model alone is suitable for growth kinetic evaluation in an aerobic biological treatment of POM wastewater (Chan et al., 2012b). Since the growth kinetics evaluation on the aerobic biomass treating POM wastewater is rarely reported, the outcome of this study will provide a better understanding on the aerobic treatment of POM wastewater and promote the usage of SBR in biological treatment of POM wastewater.