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**UNIVERSITI TEKNOLOGI PETRONAS**

# Biological Treatment of Pharmaceutical Wastewater

**By**

**Welly Herumurti**

**A THESIS**

**SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME**

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**BANDAR SERI ISKANDAR**

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**JULY, 2009**

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I would like to dedicate this to my mother, my father and my sister.

## ABSTRACT

The biological wastewater treatment study was performed to treat non-penicillin pharmaceutical wastewater. The study was conducted in two phases. The Phase I focussed on a preliminary study to determine the feasibility of biological treatment for treating pharmaceutical wastewater. The biological treatment in Phase I consisted of two treatment trains; Train 1 which consisted of a semi-anaerobic baffle reactor (SABR) followed by an activated sludge process (ASP) reactor while Train 2 consisted of only an ASP reactor. The Phase II was carried out on anaerobic treatment processes. Anaerobic biological treatment of pharmaceutical wastewater was performed using upflow anaerobic sludge blanket (UASB) and hybrid upflow anaerobic sludge blanket (HUASB) reactors. The UASB and HUASB reactors were operated under mesophilic (35±2°C) and thermophilic (55±2°C) conditions. Four hydraulic retention times (HRTs) i.e., five, four, three and two days were applied for all reactors. The sludge from an aerobic sewage treatment plant was used as seed biomass in all reactors.

In Phase I, the reactors were fed with influent chemical oxygen demand (COD) concentration of 607-1953 mg/L. Train 1 (SABR-ASP reactor) achieved higher COD removal in treating high strength wastewater (COD 1953 mg/L); however, Train 2 (ASP reactor) achieved higher COD removal in treating low strength wastewater (COD 635 mg/L). The aerobic biomass from a sewage treatment plant was successfully used as seed biomass in aerobic and semi-anaerobic reactors in treating non-penicillin pharmaceutical wastewater.

In Phase II, the reactors were fed with low strength influent (COD 458-526 mg/L) and high strength influent (COD 1770-2217 mg/L). The reactors obtained higher COD removals in treating high strength wastewater. The results show that the reactor performance was significantly affected by type of reactor, HRT and temperature. Both mesophilic UASB and HUASB reactors obtained higher COD and biochemical oxygen demand 5 days ($BOD_5$) removals in treating pharmaceutical wastewater. The highest average COD and $BOD_5$ removals were achieved by the mesophilic HUASB

reactor treating high strength pharmaceutical wastewater at HRT of five days (average OLR 0.43 g COD/L·day); average COD removal was 90%, average effluent COD was 133 mg/L, average $BOD_5$ removal was 97% and average effluent $BOD_5$ was 51 mg/L. The COD and $BOD_5$ removals decreased when the HRT was decreased. The concentration of ammonia-nitrogen ($NH_3$-N) and total phosphorous (TP) increased during this study whereas the concentration of nitrate-nitrogen ($NO_3$-N) was constant and the concentration of total Kjeldahl nitrogen (TKN) slightly reduced.

Three kinetic models i.e. Monod, modified Stover-Kincannon and Grau second-order were applied in this study to determine the kinetics of pharmaceutical wastewater treatment using UASB and HUASB reactors. The results of kinetic model analysis indicated that Grau second-order fits well for estimates of kinetic coefficients in all reactors. High $R^2$ values ($R^2$>0.9) were obtained for *a* and *b* determinations for all reactors.

## ABSTRAK

Kajian rawatan air buangan secara biologi telah diusahakan untuk merawat air buangan farmaseutikal selain daripada penisilin. Kajian telah dilakukan dalam dua fasa. Fasa pertama tertumpu pada kajian permulaan untuk menentukan kemungkinan rawatan biologi untuk merawat air buangan farmaseutikal. Rawatan secara biologi pada fasa pertama terdiri daripada dua tren rawatan; Tren 1 terdiri daripada satu "semi-anaerobic baffle reactor" (SABR) yang diikuti oleh sebuah "activated sludge process" (ASP) reaktor, sementara Tren 2 terdiri daripada satu ASP reaktor sahaja. Fasa kedua dijalankan pada proses-proses perawatan secara anaerob. Rawatan biologi anaerob air buangan farmaseutikal diusahakan menggunakan reaktor-reaktor "upflow anaerobic sludge blanket" (UASB) dan "hybrid upflow anaerobic sludge blanket" (HUASB). Reaktor UASB dan HUASB dioperasikan pada kondisi mesophilik (35±2°C) dan termophilik (55±°C). Empat waktu tinggal hidrolik (HRT) diaplikasikan pada semua reactor. Lumpur daripada satu loji rawatan air kumbahan domestik aerob digunakan sebagai benih biomasa pada semua reaktor.

Pada fasa pertama, reaktor-reaktor diisi dengan konsentrasi "chemical oxygen demand" (COD) ialah 607-1953 mg/L. Tren 1 (SABR-reaktor ASP) memperoleh penyisihan COD lebih tinggi pada rawatan air buangan konsentrasi tinggi (COD 1953 mg/L), tetapi Tren 2 memperoleh penyisihan COD lebih tinggi pada rawatan air buangan konsentrasi rendah (COD 635 mg/L). Biomasa aerob daripada satu loji rawatan air buangan domestik telah berjaya untuk digunakan sebagi benih biomasa pada reaktor-reaktor aerob dan semi-anaerob pada rawatan air buangan farmaseutikal selain daripada penisilin

Pada fasa kedua, reaktor-reaktor diisi dengan influen konsentrasi rendah (COD 458-526 mg/L) dan influen konsentrasi tinggi (COD 1770-2217 mg/L). Reaktor-reaktor mendapatkan penyisihan COD yang lebih tinggi pada rawatan air kumbahan dengan influen konsentrasi tinggi. Hasil-hasil kajian menunjukkan bahawa performa reaktor dipengaruhi secara signifikan oleh jenis reaktor, HRT dan temperatur. Reaktor UASB dan HUASB mesophilik menunjukkan penyisihan COD

dan ”biochemical oxygen demand 5 days” ($BOD_5$) yang lebih tinggi pada rawatan air buangan farmaseutikal. Purata penyisihan COD dan $BOD_5$ tertinggi diperoleh reaktor HUASB mesophilik pada penyisihan air buangan konsentrasi tinggi dengan HRT lima hari. Purata penyisihan COD ialah 90%, purata COD effluen ialah 133 mg/L, purata penyisihan $BOD_5$ ialah 97%, dan purata $BOD_5$ effluen ialah 51 mg/L Penyisihan COD dan $BOD_5$ berkurang bilamana HRT dikurangkan. Konsentrasi ammonia-nitrogen ($NH_3$-N) dan total phosphorous (TP) meningkat pada kajian ini, sedangkan konsentrasi nitrate-nitrogen ($NO_3$-N) konstan dan konsentrasi total Kjeldahl nitrogen (TKN) menunjukkan sedikit penurunan.

Tiga model kinetik, yaitu Monod, modified Stover-Kincannon, dan Grau second-order diaplikasikan pada kajian ini untuk menentukan kinetik-kinetik rawatan air buangan farmaseutikal dengan menggunakan reaktor UASB dan HUASB. Hasil kajian model kinetik menunjukkan bahawa Grau second-order sesuai untuk pengiraan koefisien kinetik pada semua reaktor. Nilai $R^2$ yang tinggi ($R^2$>0.9) didapatkan untuk penentuan *a* dan *b* untuk semua reaktor.

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## ABBREVIATIONS AND NOMENCLATURES

| | |
|---|---|
| ADS | anaerobic digester sludge |
| ASP | activated sludge process |
| AF | anaerobic filter |
| AMBR | anaerobic migrating blanket reactor |
| $BOD_5$ | biochemical oxygen demand 5 days |
| COD | chemical oxygen demand |
| HRT | hydraulic retention time |
| HUASB | hybrid up flow anaerobic sludge blanket |
| MLSS | mixed liquor suspended solids |
| MLVSS | mixed liquor volatile suspended solids |
| $NH_3$-N | ammonia nitrogen |
| $NO_3$-N | nitrate nitrogen |
| OLR | organic loading rate |
| POME | palm oil mill effluent |
| TSS | total suspended solids |
| TVSS | total volatile suspended solids |
| TKN | total Kjeldahl nitrogen |
| TP | total phosphorus |
| RAS | return activated sludge |
| SABR | semi-anaerobic baffle reactor |
| SRT | sludge retention time |
| STP | sewage treatment plant |
| UAFB | upflow anaerobic fixed bed |
| UAFF | upflow anaerobic fixed film |
| UASB | upflow anaerobic sludge blanket |
| UASFF | upflow anaerobic sludge fixed film |
| WAS | waste activated sludge |

| | |
|---|---|
| $a,b$ | kinetic constants (Grau kinetic model) |
| $K_B$ | saturation value constant (modified Stover-Kincannon), in g/L·day |
| $K_d$ | endogenous decay coefficient, in per day |
| $K_s$ | half-velocity saturation constant (mg/L) |
| $K_{s2}$ | Grau substrate removal rate constant, in per day |
| $Q$ | flow rate of influent wastewater, in L/day |
| $S_o$ | influent substrate concentration, in mg/L |
| $S_e$ | effluent substrate concentration, in mg/L |
| $U_{max}$ | maximum substrate removal rate (modified Stover-Kincannon), in g/L·day |
| $V$ | volume of reactor, in L |
| $V_b$ | volume of sludge bed, in L |
| $X$ | biomass concentration in the reactor, in mg/L |
| $X_e$ | biomass concentration of effluent wastewater, in mg/L |
| $X_o$ | biomass concentration of influent wastewater, in mg/L |
| $Y$ | cell yield coefficient, in mg VSS/mg COD |

| | |
|---|---|
| $\theta_c$ | solid retention time, in day |
| $\mu$ | specific growth rate, in per day |
| $\mu_m$ | maximum specific growth rate, in per day |
| $\theta_H$ | hydraulic retention time, in day |

# CHAPTER 1
# INTRODUCTION

## 1.1 Background

The predominance of various diseases, the growth of population and the increase of healthcare product requirements were factors that ensured a steady growth of pharmaceutical industries. In Malaysia, the requirement of cosmetics and other pharmaceutical products, e.g. vitamins and food supplements also increased. Furthermore, the Malaysian consumers who were turning from conventional drugs to herbal products increased (NPCB, 2007). Therefore, not only the penicillin pharmaceutical products, but also the non-penicillin pharmaceutical products (both quantity and type) increased. The growth of non-penicillin pharmaceutical products influenced the manufacturing processes in the pharmaceutical industry.

Raw materials used by the pharmaceutical industry might be from medicinal plants, herbs, fruits, flowers, leaves, stems, roots, gums, etc. (Nandy and Kaul, 2001). The processes involved in pharmaceutical productions can be broken down into five categories which are (a) fermentation, (b) biological and natural extractions, (c) chemical synthesis, (d) mixing, compounding and formulating and (e) pharmaceutical research (US EPA, 2006). Therefore, the composition of pharmaceutical wastewater can vary widely from one effluent to another.

It is mandatory to treat wastewater to meet effluent discharge standards before its release into the environment. Physical, chemical and biological methods are widely used in wastewater treatment. Biological treatment methods can be divided into aerobic and anaerobic types. Aerobic processes, which are widely used for wastewater treatment, at least have two distinct disadvantaged such as relatively high-energy requirement and high excess sludge production requires handling, treatment and disposal. Anaerobic processes, on the other hand, generate energy in the form of biogas and produce less sludge than aerobic processes. Therefore,

anaerobic treatment can be a lucrative alternative for treatment of pharmaceutical wastewater.

Anaerobic reactors can be influenced by environmental and/or operating conditions. Typical responses in anaerobic reactors include decrease in performance, accumulation of volatile fatty acids (VFA), drop in pH and alkalinity, change in biogas production and composition and sludge washout (Leitao et al., 2006). Methane-forming bacteria are strict anaerobes and are extremely sensitive to the presence of dissolved oxygen and changes in environmental and/or operating conditions such as alkalinity, pH and temperature. Therefore, the operation conditions must be periodically monitored and maintained within optimum ranges (Gerardi, 2003). However, there are certain unclear technical and design operation conditions which are necessary for the improvement of the stability and reliability of anaerobic treatment, especially treatment for specific wastewaters.

Several configurations of anaerobic treatment can be the alternatives for wastewater treatments system including an upflow anaerobic sludge blanket (UASB) reactor (Seghezzo, 2004). The UASB concept relies on the establishment of a dense sludge bed in the bottom of the reactor, in which all biological processes take place. The UASB reactor may replace the primary settler, the anaerobic sludge digester, the aerobic step (activated sludge, trickling filter, etc.) and the secondary settler of a conventional aerobic treatment plant. However, the effluent of UASB reactor usually needs further treatment, in order to remove remaining organic matter, nutrients and pathogens. The other configuration of anaerobic treatment is hybrid upflow anaerobic sludge blanket (HUASB) reactor. The HUASB combines the advantages of the UASB and anaerobic filter (AF) concepts. The HUASB consisting of UASB and AF has been applied to various industrial wastewater. The performance of UASB and HUASB reactors were influenced by many factors including organic loading rate (OLR), hydraulic load, sludge retention time (SRT), as well as operational temperature (Leitao, 2004). The OLR applied to the reactors depends on the influent concentration, flow rate and reactor volume; therefore also on the imposed hydraulic retention time (HRT).

Kinetic process has been used for the mathematical description of both anaerobic biological treatment processes (Seghezzo, 2004). Kinetic models of the anaerobic system can help to gain more insight into the process. The understanding of process kinetics is essential for the rational design and operation of biological wastewater treatment system and for predicting the system stability and treatment efficiency. Kinetic process plays an important role in the development and operation of anaerobic treatment systems.

## 1.2 Problem Statement

Pharmaceutical wastewater can affect the environment adversely, if discharged without proper treatment. Biological treatment is often carried out to reduce its organic content. In Malaysia, however, the use of anaerobic system for wastewater treatment is still not common. High rate anaerobic reactors such as UASB and HUASB can be attractive alternatives for pharmaceutical wastewater treatment.

## 1.3 Objectives of Study

a. To observe the performance of semi-anaerobic and aerobic reactors in treating non-penicillin pharmaceutical wastewater
b. To evaluate the performance of UASB and HUASB reactors in treating non-penicillin pharmaceutical wastewater
c. To evaluate the effect of HRT and temperature on the performance of UASB and HUASB reactors
d. To determine the kinetics of pharmaceutical wastewater treatment using UASB and HUASB reactors

## 1.4 Scope of Study

This study presents the performance of biological treatment, specifically anaerobic treatment for treating non-penicillin pharmaceutical wastewater. The study was divided into two phases. The first phase was conducted to observe the performance of semi-anaerobic and aerobic system. The second phase evaluated the anaerobic

treatment using UASB and HUASB reactors. Wastewater used in this study was taken from a non-penicillin based factory.

The study focused on the operating conditions of anaerobic treatment (i.e. HRT and temperature) and highlighted the use of different type of anaerobic reactors. The experimental investigation was performed using four bench-scale reactors. The two UASB reactors and two HUASB reactors were operated under mesophilic and thermophilic temperatures. The seed biomass for the reactors was taken from aerobic based sewage treatment plant.

## 1.5 Thesis Organisation

This thesis has been organized into the following five chapters:

Chapter 1 introduces the context of study about non-penicillin pharmaceutical wastewater biological treatment. Problem statement, objectives and scope of the study are presented in this chapter.

Chapter 2 presents a brief review of pharmaceutical wastewater and biological treatment to treat pharmaceutical wastewater. Factors that effect anaerobic treatment and reactor configurations are also reviewed in this chapter.

Chapter 3 presents the methodology of study that was applied to treat non-penicillin pharmaceutical wastewater.

Chapter 4 shows the results viz. Phase I used semi-anaerobic and aerobic treatment and Phase II was based on UASB and HUASB reactors. The experiment results are also discussed.

Chapter 5 summarizes the findings of the study on non-penicillin pharmaceutical wastewater biological treatment.

# CHAPTER 2
# LITERATURE REVIEW

This chapter presents a brief review of pharmaceutical wastewater. Basic concepts and theories of biological treatment, especially anaerobic treatment are also introduced.

## 2.1 Pharmaceutical Wastewater

The prevalence of various diseases, the growth of population and the increase of healthcare needs were factors that ensured a steady growth of pharmaceutical industry. The key drivers that boosted the Malaysian pharmaceutical industries are medical tourism, specialist therapy, generic and over-the-counter drugs and food supplements. The current self-managing trend among Malaysian consumers is a major factor that has broadened the over-the-counter drug market, which is mainly driven by vitamin and dietary supplements. Malaysian consumers who are turning from synthetic allopathic drugs (conventional drugs) to herbal products to maintain health and prevent illnesses are on the increase (Kok, 2008).

In the year 2007, 27974 product registration applications were received by the National Pharmaceutical Control Bureau (NPCB) Malaysia that was established to implement quality control testing of pharmaceutical products. The numbers of prescription drugs, non-prescription drugs, traditional products and cosmetics registered by the Drug Control Authority (DCA) of NPCB were 449, 413, 1342 and 28403, respectively. Manufacturers layout plants which consist of 7 prescription manufacturers, 7 non prescription manufacturers, 13 traditional manufacturers, 10 cosmetic manufacturers and 2 veterinary manufacturers were evaluated by the Good Manufacturing Practices (GMP) of NPCB and a total of 301 manufacture licences were issued in the year 2007 (NPCB, 2007).

The composition of wastewater from industrial operations varies widely depending on the function and activity of the particular industry. Because of variation of flow rate

and water quality, it is often difficult to define the operation conditions for industrial activities (Metcalf & Eddy, 2003). Pharmaceutical industry includes manufacture, extraction, processing, purification and packaging chemical materials that are used as medications for humans or animals. Pharmaceutical manufacturing can be divided into two major stages: production of the active ingredient or drug and secondary processing or conversion of the active drugs into products suitable for administration (Cheremisinoff, 2001).

The major manufactured groups include:

a. Antibiotics such as penicillin, streptomycin, tetracyclines, chloramphenicol and antifungal
b. Other synthetic drugs, including sulfa drugs, anti-tuberculosis drugs, anti-leprotic drugs, analgesics, anesthetics and anti-malarials
c. Vitamins
d. Synthetic hormones
e. Glandular products drugs of vegetable origin, such as quinine, strychnine and brucine, emetine and digitalis glycosides
f. Vaccines and sera
g. Other pharmaceutical chemicals

Their composition varies, depending on the product manufactured, the materials used in the process and other process details (Cheremisinoff, 2001).

Pharmaceutical wastewater, which include several organic solvents and other toxic chemicals, are generally treated aerobically. The alternative treatment is the anaerobic route that has lower cost of treatment and generates methane gas that can be used as energy. However, there are few reports on the anaerobic treatment of the pharmaceutical effluents. The most important merits of anaerobic treatment are the ability to treat high strength wastewater, low energy and space requirement, low sludge production, low operation cost and net benefit of energy generation. The production of biogas in the anaerobic organic degradation makes this process a feasible alternative to aerobic treatment methodology (Mohan et al., 2001).

The raw material used by the pharmaceutical factory might be from medicinal plants, herbs, fruits, flowers, leaves, stems, roots, seeds, gums, etc. In almost all pharmaceutical industries, the production processes are in batches. Therefore, the processes have a lack of homogeneity that leads to variation in wastewater quality and quantity. The wide fluctuations on the treatment units in terms of organic and hydraulic loadings might have a harmful effect on anaerobic processes and cause destabilization of the microbial populations leading to volatile fatty acids (VFA) accumulation that can acidify the reactor and inhibit methanogenic microorganisms (Nandy and Kaul, 2001).

## 2.2 Biological Wastewater Treatment

Biological methods of wastewater treatment can be either aerobic (in the presence of oxygen) or anaerobic (in the absence of oxygen). Aerobic processes, which are widely used for wastewater treatment, at least have two distinct disadvantages viz., relatively high-energy requirement and high excess sludge production. Excess sludge production requires handling, treatment and disposal. Anaerobic processes generate energy in the form of biogas (methane) and produce less sludge than aerobic processes. However, a certain prejudice against using anaerobic processes exists in tropical countries. Another reason is a serious lack of knowledge by the engineers on the design and operation of anaerobic systems (Seghezzo, 2004). The main advantages and drawbacks of anaerobic treatment are shown in Table 2.1 (Hall, 1992; Lettinga, 1996; Seghezzo, 2004; Seghezzo et al., 1998).

### 2.2.1 Anaerobic Process

Three different groups of bacteria are involved in the transformation of complex organics into simple molecules such as methane and carbon dioxide (Wiesmann et al., 2007). They are involved in three basic steps in the complete anaerobic oxidation process: hydrolysis, fermentation (also known as acidogenesis) and methanogenesis (Metcalf & Eddy, 2003; Vaccari et al., 2006). The three steps are illustrated schematically in Figure 2.1.

Table 2.1 Advantages and disadvantages of anaerobic treatment

| Advantages |
|---|
| a. Low biological sludge production. The excess sludge is generally significantly lower than aerobic process, due to the slow growth rates of anaerobic bacteria. The excess sludge is generally well stabilized. |
| b. High treatment efficiency. High removal efficiency can be achieved in anaerobic process, even at high organic loading rate (OLR). The anaerobic treatment is feasible for a wide range of waste and wastewater, i.e. complex in composition, a low and very high strength, low and high temperatures |
| c. Low energy consumption, As long as no heating requirement is needed to reach the operational temperature and all reactor operations can be operated by gravity, the energy consumption for the reactor is almost negligible. |
| d. Methane production. Instead of consuming energy, biogas is produced. |
| e. Low nutrient and chemical requirements. An adequate and stable pH can be maintained without the addition of chemical. |
| f. Valuable nutrients (nitrogen and phosphorus) are conserved which give high potential for irrigation. |
| g. Low space requirement. When high OLR are applied, the area requirement for anaerobic reactor is small. |
| h. Anaerobic biomass can be preserved without feeding for long period without any serious deterioration of their activity. |
| i. Simple and flexible. The construction and operation of anaerobic reactor is relatively simple and can be applied on either a very large or a small scale. |
| **Disadvantages** |
| a. Low nutrient and pathogen removal. Nutrient removal is negligible and pathogens are only partially removed, especially when the anaerobic reactor is operated in low temperature. |
| b. Require post treatment. Post treatment of the anaerobic effluent is generally required to achieve the discharge standard for organic matter, nutrients and pathogens. |
| c. Long start-up. Due to the low growth rate of methanogenic organism, the start up takes longer as compared to aerobic processes, especially when no good inoculums is available. |
| d. Possible bad odours. Hydrogen sulphide is produced during the anaerobic process, especially when there are high concentrations of sulphate in the wastewater. |
| e. Require capable operators. The anaerobic reactor should be sufficiently understood by engineers and operators. |

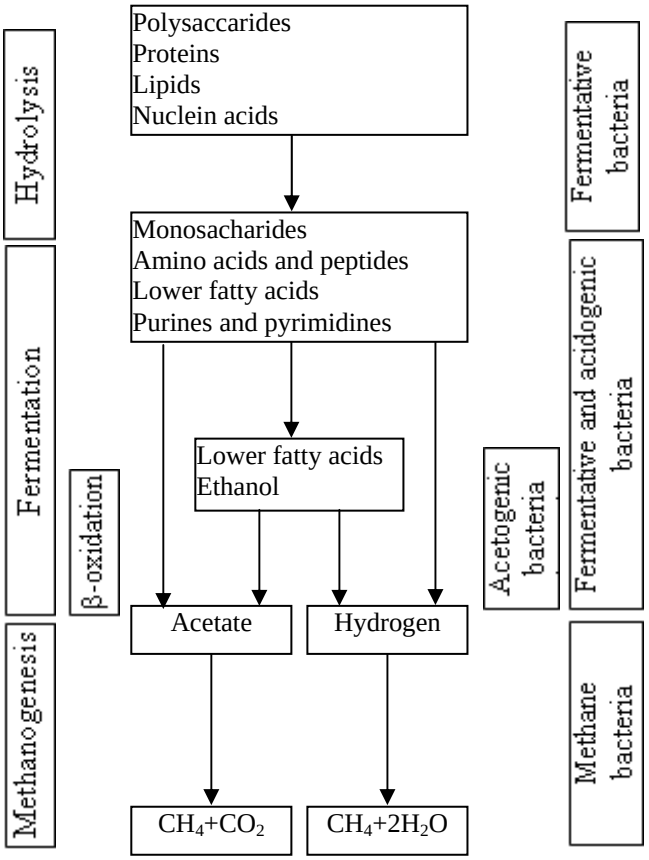


Figure 2.1 Anaerobic process schematic
(Metcalf & Eddy, 2003; Wiesmann et al., 2007)

The first step for most fermentation is hydrolysis in which particulate material is converted to soluble compounds that can then be hydrolyzed further to simple monomers. The monomers are used by bacteria that perform fermentation (Metcalf & Eddy, 2003). During hydrolysis step, macromolecular organic compounds entering the system are transformed hydrolytically from large and in many instances solid phase macromolecular materials (e.g., cellulose, grease, protein, microbial cells) into their smaller, soluble building blocks (e.g., amino acids released from protein, carbohydrates from polysaccharides, fatty acids from lipids and fats) (Vaccari et al., 2006). The monomers are directly available to the next group of bacteria (Bitton, 2005). During subsequent fermentation maintained by the anaerobic digestion process, one fraction of these hydrolyzed organics will eventually be oxidized to carbon dioxide, another fraction will be reductively converted to methane

and a third, comparatively smaller fraction will be assimilated anabolically into a new anaerobic cell mass (Vaccari et al., 2006).

The second step is fermentation where in amino acids, sugar and some fatty acids are degraded further (Metcalf & Eddy, 2003). Two different types of acidogenic reactions are involved: one and two-step conversions. The first mechanism produces acetate primarily (i.e., by means of an acetogenic conversion, encompassing reactions that produce organic acids directly). The second fermentative conversion involves intermediate production of volatile fatty acids (e.g., butyric and proprionic acid) and alcohols, which are converted subsequently to acetate, hydrogen and carbon dioxide (Vaccari et al., 2006). Acidogenic bacteria produce extracellular enzymes (exoenzymes) for the hydrolysis of complex organic molecules. Carbohydrates are hydrolyzed down to monosaccharide and disaccharides, proteins into amino acids and lipids into fatty acids. These compounds are transformed to acetate and longer chain fatty acids as well as $CO_2$ and $H_2$. The most important organics in wastewater are proteins, lipids and hydrocarbons. All can be utilized by acidogenic bacteria, which encompass a very large group of different, mostly facultative anaerobic bacteria (Wiesmann et al., 2007).

Proteins are hydrolyzed into amino acids by proteases, which function as exo-enzymes. A small amount of amino acids is used directly for growth (anabolism), while a large amount is converted to lower fatty acids, $CO_2$, $H_2$ as well as $NH_4^+$ and is excreted (catabolism). Lipids are esters formed from glycerine, an alcohol with valence of three and fatty acids. These have been hydrolyzed previously by lipase enzymes. Glycerine can be partially used for anabolic reactions and is converted in part to lower alcohols (catabolism). Fatty acids cannot be used by acidogenic bacteria and are excreted. One part is totally used for protein synthesis and bacterial growth, while another part is converted into lower fatty acids (Wiesmann et al., 2007).

Acetogenic bacteria transform lower fatty acids such as butyrate and propionate into acetate, $CO_2$ and $H_2$. It is of great importance that $H_2$ is oxidized by other anaerobic

bacteria. Otherwise, propionate concentrations would continually increase. Only a part of acetate is formed directly during fermentation (Wiesmann et al., 2007).

The third step, methanogenesis, is carried out by a group of methanogenic organisms (Metcalf & Eddy, 2003). Methanogenesis converts low molecular weight organic precursor species into gaseous end products at both ends of the carbon oxidation state range, including fully reduced methane and fully oxidized carbon dioxide. At this point, therefore, the overall process of anaerobic digestion will have biochemically converted a sizable fraction of an initial sludge residual into a far more kindly, possibly even energetically useful gaseous product (Vaccari et al., 2006).

Hydrogen and acetate must be utilized by methanogenic bacteria. They exhibit two main products of catabolic metabolism (Wiesmann et al., 2007). Two groups of methanogens are involved in methane production. One group, termed aceticlastic methanogens, split acetate into methane and carbon dioxide. The other group, termed hydrogen-utilizing methanogens, use hydrogen as the electron donor and $CO_2$ as the electron acceptor to produce methane. Anaerobic bacteria, termed acetogens, are also able to use $CO_2$ to oxidize hydrogen and form acetic acid. However, the acetic acid will be converted to methane, so the impact of this reaction is minor (Metcalf & Eddy, 2003).

Methane is not very soluble in water and carbon dioxide is in equilibrium with $HCO_3^-$ and $CO_3^{2-}$ as a function of pH. Most of the $CO_2$ and nearly all of the methane produced are desorbed, forming biogas bubbles, which can be recovered for utilization. Lower fatty acids such as butyrate and propionate can only be mineralized if the two catabolic products of acetogenic bacteria, i.e. hydrogen and acetate, are consumed by methanogenic bacteria. The methanogens are very old microorganisms, living on earth since before the oxygen-rich atmosphere was formed (Wiesmann et al., 2007).

The by-product from the anaerobic decomposition of organic matter in wastewater is methane gas. Normally, large quantities are not encountered in untreated wastewater

because even small amounts of oxygen tend to be toxic to the organisms responsible for the production of methane (Metcalf & Eddy, 2003).

## 2.3 Factors Affecting Anaerobic Treatment

Methane-forming bacteria are strict anaerobes and are extremely sensitive to changes in environmental and/or operation conditions such as alkalinity, pH and temperature. Therefore, the operation conditions must be periodically monitored and maintained within optimum ranges (Gerardi, 2003).

### 2.3.1 pH and Alkalinity

Most methanogens function well in a pH range of 6.7 to 7.4, but optimally at pH of 7.0 to 7.2 and the process may fail if the pH is close to 6.0. Acidogenic bacteria produce organic acids that decrease the pH of the bioreactor. Under normal operating conditions, this pH reduction is buffered by bicarbonate produced by methanogens. Under poor environmental conditions, the buffering capacity of the system can be upset, eventually stopping methane production. Acidity has more inhibitory effect to methanogens than to acidogenic bacteria. An increase in volatile acids level thus serves as an early indicator of system upset. The ratio of total volatile acids (as acetic acid) to total alkalinity (as calcium carbonate) has been suggested to be maintained below 0.1 (Bitton, 2005).

Alkalinity in wastewater results from the presence of the hydroxides ($OH^-$), carbonates ($CO_3^{2-}$) and bicarbonates ($HCO_3^-$) of substances such as calcium, magnesium, sodium, potassium and ammonia. Borates, silicates, phosphates and similar compounds can also contribute to alkalinity (Metcalf & Eddy, 2003). One method for restoring the pH balance is to increase alkalinity by adding chemicals such as lime, anhydrous ammonia, sodium hydroxide, or sodium bicarbonate (Bitton, 2005). Alkalinity helps to resist changes in pH caused by the addition of acids. It is determined by titrating against a standard acid. In practice, alkalinity is expressed in terms of calcium carbonate ($CaCO_3$) (Metcalf & Eddy, 2003).

The most significant negative factor that can affect the economics of anaerobic versus aerobic treatment is the possible need to add alkalinity. Alkalinity concentrations of 2000 to 3000 mg/L as $CaCO_3$ may be added in anaerobic processes to maintain an acceptable pH with the high gas phase $CO_2$ concentration. If the amount of alkalinity is not available in the influent wastewater or can not be produced by the degradation of protein and amino acid, a significant cost may be incurred to purchase alkalinity, which can affect the overall economic of the process (Metcalf & Eddy, 2003).

With the high $CO_2$ content (typically in the range from 30 to 50 percent) in the gas produced in anaerobic treatment, alkalinity concentration in the range from 2000 to 4000 mg/L as $CaCO_3$ is typically required to maintain the pH at or near neutral (Metcalf & Eddy, 2003).

### 2.3.2 Temperature

Temperature is very important in assessing the overall efficiency of a biological treatment process. Temperature not only influences the metabolic activities in the microbial population but also has a strong effect on gas-transfer rates (Seghezzo, 2004). There are two optimal ranges for process operation to produce methane: from 30 to 40°C (the mesophilic range is from 15 to 40°C) and 50 to 60°C (the thermophilic range is for temperatures above 40°C). The psychrophilic range is temperatures below 15 to 20°C (Droste, 1997). Methane production has been documented under a wide range of temperatures ranging between 0°C and 97°C (Bitton, 2005). Methane has been produced at temperatures down to 10°C or lower, but for reasonable rates of methane production, temperatures should be maintained above 20°C. Rates of methane production approximately double for each 10°C temperature rise (Droste, 1997). Reactor temperatures of 25 to 35°C are generally preferred to support optimal biological reaction rate and to provide stable treatment (Metcalf & Eddy, 2003). Methanogens are very sensitive to even small changes in temperature. Thus, mesophilic digesters must be designed to operate at a temperature of 30 to 35°C for their optimal functioning. As regards the utilization of volatile acids by methanogens, a decrease in temperature leads to a decrease of the maximum

specific growth rate ($\mu_{max}$), while the half-saturation constant $K_s$ increases (Bitton, 2005).

Loading rates must decrease as temperature decreases to maintain the same extent of treatment (Droste, 1997). Thermophilic treatment allows higher loading rates and is also beneficial to greater destruction of pathogens (Bitton, 2005). However, operation in the thermophilic range is not generally practical because of the high heating energy requirement (Droste, 1997).

### 2.3.3 Hydraulic Retention Time (HRT)

The operating hydraulic retention time (HRT), which depends on wastewater characteristics and environmental conditions, must be sufficient to allow metabolism by anaerobic microorganisms in digesters (Bitton, 2005).

### 2.3.4 Chemical Composition of Wastewater

There are significant differences in nutrient requirements between aerobic and anaerobic biological treatment processes. These differences are due to the unique needs of methane-forming bacteria and the lower cell (sludge) yield of fermentative bacteria as compared to aerobic bacteria. These two treatment requirements may be grouped as macronutrients and micronutrients. Macronutrient requirement for anaerobic biological treatment processes are much lower than the requirement for aerobic biological treatment (Gerardi, 2003).

Phosphorus is important in cellular energy transfer mechanisms via adenosine triphosphate (ATP) and polyphosphates. Biological phosphorus removal is realized by creating conditions favorable for the growth of phosphate-accumulating organisms (PAOs). The PAOs assimilate acetate and produce intracellular polyhydroxybutyrate (PHB) storage product using energy available from stored polyphosphate. An initial anaerobic zone allows the PAOs to take up VFAs into their cells and store them as PHB. The polyphosphate stored just prior to this is oxidized and used as an energy source, producing ATP; and it is thereby released into the liquid phase (Figure 2.2).

The anaerobic uptake of organic matter is inherently related to the accumulated polyphosphate. Some glycogen that contained in the cell is also used. Concurrent with the acetate uptake is the release of orthophosphate ($O\text{-}PO_4$), as well as magnesium, potassium and calcium cations. The PHB content in the PAOs increases while the polyphosphate decreases (Metcalf & Eddy, 2003; Wiesmann et al., 2007).

In anaerobic zone, concentrations of orthophosphate as high as 40 mg/L can be measured in the liquid as compared to wastewater influent concentration of 5 to 8 mg/L. The high concentration of $O\text{-}PO_4$ can be taken as indication that phosphorus release by the bacteria has occurred in this zone. Significant amounts of poly-β-hydroxybutyrate (PHB) are found stored in bacteria cells (Metcalf & Eddy, 2003).

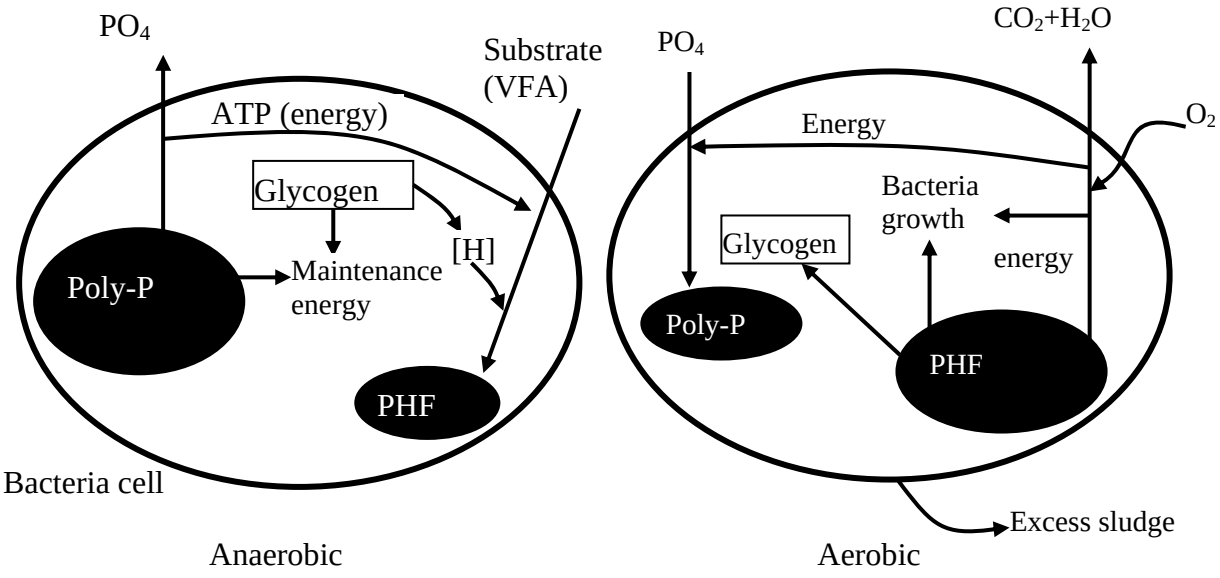


Figure 2.2 Mechanism of biological phosphorus removal
(Wiesmann et al., 2007)

## 2.4 Upflow Anaerobic Sludge Blanket (UASB) Reactor

The UASB process uses suspended biomass, but the gas-liquid-solids separation system is integral with the bioreactor. More importantly, the environmental conditions created in the bioreactor can result in the development of large, dense, readily settleable particles called granules, which allow very high concentrations of

suspended solids to be accumulated. These high suspended solids concentrations allow significant separation between the sludge retention time (SRT) and HRT and operation at relatively short HRT, often on the order of two days or less (Grady et al., 1999).

Influent wastewater enters the bottom of the bioreactor through a distribution system that is designed to provide relatively uniform flow across its cross section. A dense slurry of granules forms in the lower portion of the bioreactor and the combined effects of the influent wastewater distribution and gas production result in mixing of the influent wastewater with the granules. Treatment occurs within the dense blanket of granules (Grady et al., 1999). Inside these porous particles, fatty acids and biogas are formed. The reaction rate of the process is controlled by diffusion, convection and reaction inside the pores. Ascending biogas bubbles keep the particles partially fluidized (Wiesmann et al., 2007). For some wastewaters, a much less dense flocculent sludge also develops and this accumulates on top of the blanket of granules. Other wastewaters contain suspended solids that are not trapped in the granular sludge and these solids also accumulate as a flocculent sludge blanket overlying the granules (Grady et al., 1999).

The treated effluent exits the granular and flocculent sludge zones and flows upward into the gas-liquid-solids separator. A variety of configurations can be used for this device. The device often consists of a gas collection hood with a settler section above it (Grady et al., 1999). At the top of the UASB, the gas bubbles are separated from the water in hoods and the rising flocs, which show a lower settling rate, are carried up by the gas/liquid flow. Gas is collected in the hoods and removed (Wiesmann et al., 2007). Gas bubbles cause some granular and flocculent solids (particularly small granules) to rise through the bioreactor and enter the gas-liquid-solids separator. Gas separation occurs in the hood area, thereby allowing some of this suspended material to return directly to the solids blanket. Gas collects is in the upper inverted V section of the hood and is removed from the bioreactor. Liquid with some entrained solids flows out of the hood into the settler section where liquid-solids separation occurs. Clarified effluent overflows to the weirs and effluent is discharged

while separated solids settle back into the reaction zone. Design of the gas-liquid-solids separation device requires insight into the physical processes occurring there and experience with specific devices in a variety of applications (Grady et al., 1999). The example of UASB schematic diagram is shown in Figure 2.3.

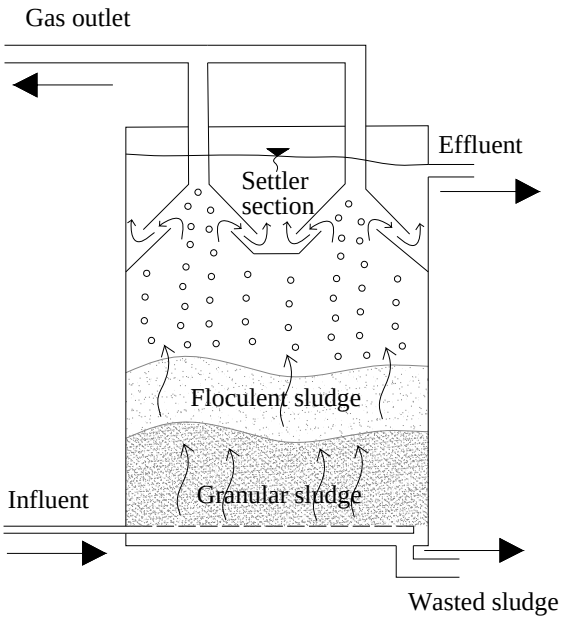


Figure 2.3 UASB Reactor
(Grady et al., 1999; Wiesmann et al., 2007)

## 2.5 Hybrid Uplow Anaerobic Sludge Blanket (HUASB) Reactor

Biofilm reactors utilize a fixed film approach for efficient anaerobic treatment of wastewater. Support media (rock, gravel, plastics, etc.) or biomass carrier is added to favour the microorganisms growth on the surface of media (Bitton, 2005; Wiesmann et al., 2007). The bulk of anaerobic microorganisms grow attached to the filter media; however, some form flocs that become trapped inside the filter media. The upflow system in the reactor helps to retain suspended solids in the column. The physical attachment prevents biomass washout, hence it leads to high values of sludge concentration and SRT. The example of anaerobic fixed film and HUASB reactors schematic diagram is shown in
Figure 2.4.

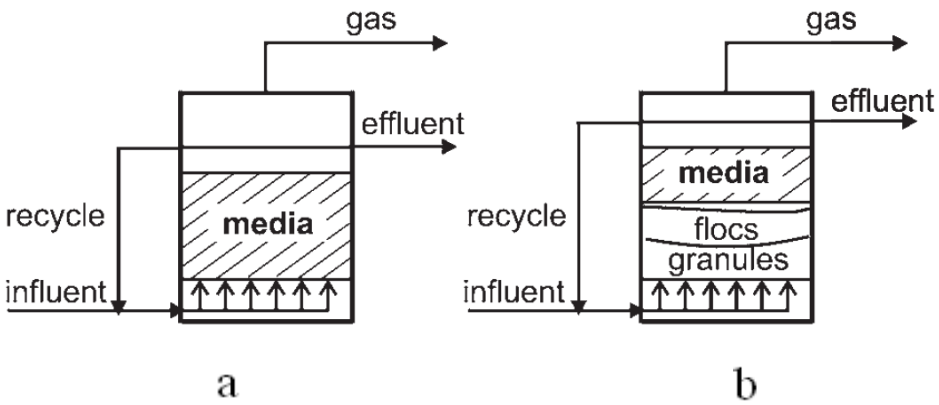


Figure 2.4 (a) Anaerobic fixed film reactor and (b) HUASB reactor (Wiesmann et al., 2007)

The HUASB combines the advantages of the UASB and anaerobic filter concepts. The HUASB consisting of UASB and AF has been applied to various industrial wastewater such as palm oil mill effluent (POME) (Najafpour et al., 2006), chemical synthesis pharmaceutical (Oktem et al., 2007), complex phenolic mixture simulated coal (Ramakrishnan and Gupta, 2008), bulk drug pharmaceutical (Sreekanth et al., 2009), etc. On the top of an UASB reactor, a fixed bed reactor with a relatively short bed of synthetic media is installed and it was operated as HUASB reactor (Wiesmann et al., 2007). The HUASB reactors could also become a preferred option for pharmaceutical wastewater due to its operation, advantages over other reactor configurations (Oktem et al., 2007).

## 2.6 Pharmaceutical Wastewater Anaerobic Treatment

Table 2.2 shows the previous studies on anaerobic treatment of pharmaceutical wastewater. Oktem et al. (2007) studied the performance of a lab-scale HUASB reactor treating pharmaceutical wastewater. The pharmaceutical wastewater was collected from a chemical synthesis based pharmaceutical factory, whose main products were bacampicilline and sultampicilline tosylate. The HUASB consisted of a UASB portion and an anaerobic filter portion and was operated under different operating conditions. Polypropylene pall rings were used as filter media. The reactor was seeded by a granular sludge taken from a full-scale UASB reactor treating an alcohol distilling industry wastewater.

Table 2.2 Pharmaceutical wastewater treatment studies

| Type of treatment | Temp (°C) | Wastewater | HRT | Initial COD (mg/L) | Removal COD (%) | Reference |
|---|---|---|---|---|---|---|
| UASB and activated sludge (semi-pilot plant) | 30 | Biosynthetic pharmaceutical | 2.3 d | 7140-10410 | 92.2% (UASB) | (Jenicek et al., 1996) |
| UAFF (bench scale) | 35 | Herbal based pharmaceutical | 6, 5, 1.5, 1.25 d and 20 h | 5000-80000 | 76-98 | (Nandy and Kaul, 2001) |
| HUASB (UASB-AF) (bench scale) | N/S | Chemical synthesis based pharmaceutical | 1-3 d | 6000-27000 | 65-83 | (Oktem et al., 2007) |
| HUASB (UASB-AF) (bench scale) | 55±3 | Bulk drug pharmaceutical | N/S | 13000-15000 (OLR 1-12 g COD/L) | 65-75 | (Sreekanth et al., 2009) |
| Anaerobic batch reactor | 37 | Pharmaceutical, brewery, paper and amino acid producing industries (diluted) | | 1950-9230 | | (Martinez et al., 2005) |
| Anaerobic suspended film contact (bench scale) | 35±2 | Bulk drug manufacturing | 8 d | 23700-24500 | 30-82 | (Mohan et al., 2001) |
| Expanded granular sludge bed anaerobic reactor | 15 | Pharmaceutical containing solvent | 48, 24, 12 and 6 h. | 5-20 kg COD/$m^3$ day (OLR) | 60-80 | (Enright et al., 2005) |

Table 2.2 (Continued)

| Type of treatment | Temp (°C) | Wastewater | HRT | Initial COD (mg/L) | Removal COD (%) | Reference |
|---|---|---|---|---|---|---|
| Packed bed anaerobic (bench scale) | 35±2 | Organic synthesis pharmaceutical | N/S | 23000-31000 mg/L | 80-98 | (Nacheva et al., 2006) |
| Aerobic biological treatment (batch reactor) | 30-70 C | Pharmaceutical (untreated) | 96 h | 7320±160 | 38-62% (30 C-60 C) | (Lapara et al., 2001) |
| Anaerobic baffled reactor[a] and biofilm airlift suspension reactor[b] (pilot scale) | 35 C | Antibiotic pharmaceutical | 1.25 d and 2.5 d[a]; 5.0-12.5 h[b] | 9736-19862 | 87% | (Zhou et al., 2006) |

The OLR was gradually increased from 3 to 9 kg COD/$m^3$·day to determine the relationship between COD removal and OLR in HUASB reactor. The COD removal efficiency was found to decrease gradually with increase in OLR. The COD removal efficiencies of 83% and 79% were achieved at OLR of 4 kg COD/$m^3$·day and 5 kg COD/$m^3$·day, respectively. Moreover, at the OLR of 6 kg COD/$m^3$·day and HRT of two days, the COD removal efficiency was 75%. When the OLR increased from 6 to 7 kg COD/$m^3$·day, the HUASB reactor performance did not decline significantly. On the other hand, when the OLR increased from 8 to 9 kg COD/$m^3$·day, the COD removal efficiency showed a drastic decrease from 65 to 28% (Oktem et al., 2007).

Sreekanth et al. (2009) investigated the performance of a thermophilic HUASB reactor at different OLRs. The HUASB reactor was used to treat wastewater from a bulk drug pharmaceutical industry whose main product was terbinafine hydrochloride. A 17 L lab scale HUASB reactor with PVC rings at the middle of the reactor was used. The seed sludge was taken from a full-scale UASB reactor that treated a slaughterhouse wastewater. The COD concentration varied from 13000 to 15000 mg/L and $BOD_5$ concentration varied from 7000 to 7500 mg/L. The BOD: COD ratio ranged from 0.45 to 0.6, which was pleasant to biological treatment.

The HUASB reactor was studied at different OLRs. The COD and $BOD_5$ removals ranged from 65 to 75% and 80 to 94%, respectively, were obtained at the optimum OLR of 9 kg COD/$m^3$·d. The methane content ranged from 60 to 70% and specific methanogenic activity (SMA) was 320 mL $CH_4$/g VSS·d. The biogas production ranged from 300 to 500 mL/g COD. Sreekanth et al. reported that the VFA concentrations varied from 100 to 400 mg/L as acetic acid at the OLR of 1 to 11 g COD/L·day, respectively. It indicated no loss of methanogenic potential in the mixed biomass. However, when the OLR increased suddenly from 2 to 5 g COD/L·day, the VFA concentration also increased from 400 to 2500 mg/L as acetic acid. It indicated methanogenic inhibition due to toxicity of bulk drug industrial effluent.

The application of hybrid reactors to the treatment of pharmaceutical wastewater is limited. No study was carried out on the thermophilic treatment of bulk drug pharmaceutical wastewater, although thermophilic process offers several benefits such as an increased degradation rate for organic solids, a high gas production rate, improved solid liquid separation, increased disinfection of pathogenic organisms and eliminating the cooling process for effluent of high temperature wastewater.

Jenicek et al. (1996) reported the anaerobic treatment of biosynthetic pharmaceutical wastewater using a semi pilot scale UASB reactor and an activated sludge system. The UASB reactor was operated at 30°C and obtained a COD removal of 92.2%. The residual COD in the anaerobic effluent was about 800 mg/L. Moreover, the UASB and activated sludge process obtained the COD removal of 97.5% at HRT of 2.3 days. The average COD and $BOD_5$ concentrations were 7140 and 4500 mg/L, respectively. The $BOD_5$/COD ratio was 0.63, which was relatively high and indicated good biodegradability. Jernicek et al. (2001) also reported that in the pharmaceutical factory, the fluctuation of the wastewater characteristics was very high (COD 2500-31500 mg/L).

Biotreatability of pharmaceutical wastewater using an anaerobic suspended film contact reactor was studied by Mohan et al. (2001). The reactor was designed to achieve effective contact with the anaerobic biomass in suspended form with the organic load. The $BOD_5$/COD ratio of the pharmaceutical wastewater from a large bulk drug-manufacturing unit was in the range of 0.4 to 0.6, which is amenable to anaerobic treatment. The reactor was operated at HRT of eight days with a working volume of 8 L. Mohan et al. (2001) confirmed that the increase in OLR from 2 to 10 g COD/day increased the COD removal rate. The COD removal ranged from 30 to 82%. However, at OLR of 20 g COD/day, the COD removal decreased. This was attributed to the micro toxic effect of high organic load on the microorganisms. The pH value of the effluent ranged from 6.8 to 8.2, which were well within the optimum pH range for methanogenesis. The methane content in the reactor was

found to be 60 to 70%. The gas analysis showed it was composed of 70% methane, 26% $CO_2$ and 4% $N_2$ (Mohan et al., 2001).

Applicability of anaerobic treatment of herbal-based pharmaceutical wastewater was studied at laboratory-scale by Nandy and Kaul (2001). An upflow anaerobic fixed film (UAFF) reactor was used to treat influent COD concentration of 5000-80000 mg/L. The COD removals ranged from 70 to 97% and 58 to 94% at HRTs of 5 and 2.5 days, respectively. The UAFF reactor was operated at 35°C. Herbal pharmaceutical wastewater distinguishes itself due to its high content of organic pollutant and its high acidic nature. Among the wide range of anaerobic reactor systems developed for the treatment of high strength wastewaters, UAFF reactor system has emerged with more successful operation (Nandy and Kaul, 2001).

Biological degradation of organic synthesis pharmaceutical wastewater was studied by Nacheva et al. (2006) using packed bed anaerobic mesophilic reactors. The pharmaceutical wastewater contained high organic matter and very low TSS. Five different support materials were used in the anaerobic reactor to treat pharmaceutical wastewater with influent COD concentration of 23000 to 31000 mg/L at temperature of 35±2°C. The reactors were fed with wastewater from organic synthesis processes that were performed in a chemical pharmaceutical plant. COD removal of 80 to 90% was obtained in the reactors with sand, anthracite and black tezontle at OLR of 3.6 $kg/m^3 \cdot day$. Whereas, the reactor with granular activated carbon (GAC) had a better performance, which had COD removal higher than 95% and 80% at OLR of 17 and 26 $kg/m^3 \cdot day$, respectively. The reactor that used GAC as support material, obtained greater biodegradation rates than the rest of the materials and process was more resistant to organic load increases, inhibition effects and toxicity (Nacheva et al., 2006).

Enright et al. (2005) studied low temperature anaerobic biological treatment of solvent containing pharmaceutical wastewater. Two identical expanded granular sludge bed (ESGB) anaerobic reactors were operated at 15°C and OLR of 5 to 20 kg $COD/m^3 \cdot day$. COD removal efficiencies of 60-70% were achieved in these

studies. The reactors were operated at HRTs of 48, 24, 12 and 6 hours and the COD removal increased from 78 to 85% at a decreasing HRT of 48-24 hours. However, the COD removal decreased while the HRTs were decreased from 24 to 12 hours and 12 to 6 hours. The methane content decreased with decreasing HRT (Enright et al., 2005).

An active methanogenic biomass developed with a rapid start up with seeded sludge from an anaerobic reactor treating citric acid production wastewater and from an anaerobic reactor treating industrial alcohol production wastewater, even though the seed sludge was taken from different operation temperatures. Overall, the results of the study indicated the feasibility of psychrophilic (<20°C) treatment of pharmaceutical solvent containing.

Anaerobic and aerobic treatment of high strength pharmaceutical wastewater was evaluated by Zhou et al (2006). A batch test was performed to study the biodegradability of wastewater and based on the batch test, a pilot scale system composed of anaerobic baffled reactor followed by a biofilm airlift suspension reactor was conducted. The anaerobic bioreactor was operated at the temperature of 35°C and the influent COD influent ranged from 9736 to 19862 mg/L. The anaerobic baffled reactor results showed the effluent COD ranged from 1432 to 2397 mg/L at HRT of 1.25 day and 979 to 1749 mg/L at HRT of 2.5 day, respectively. On the other hand, the effluent from the aerobic reactor varied between 256 and 355 mg/L at HRTs of 5 to 12.5 hours. The wastewater also contained antibiotic substances with ampicillin and aureomycin concentrations of 3.2 and 1.0 mg/L, respectively. The anaerobic bioreactor could partially degrade the antibiotics while the aerobic reactors showed insignificant antibiotics removal. The ampicillin and aureomycin removal efficiencies in the anaerobic reactor were 16.4% and 25.9% at HRT of 1.25 days and 42.1% and 31.3% at HRT of 2.5 days, respectively, while in the aerobic reactor, the removal efficiencies of the antibiotics were less than 10% (Zhou et al., 2006).

The effect of temperature in aerobic biological pharmaceutical wastewater treatment was studied by Lapara et al. (2001) using batch reactors. The reactors were operated

at 5°C intervals from 30 to 70°C. Soluble COD removal efficiency declined as temperature increased from 30 (62%) to 60°C (38%). Aerobic biological treatment failed to occur at temperature higher than 60°C (Lapara et al., 2001).

## 2.7 Anaerobic Reactor Seeded with Aerobic Sludge

Due to limited number of thermophilic anaerobic digesters in operation, it was often difficult to start up a new one using sludge from an existing reactor as seed. However, most researchers consider mesophilic anaerobic sludge to be a satisfactory inoculum for the thermophilic anaerobic reactor, because it is grown in a similar anaerobic environment (Kim and Speece, 2002).

Kim and Speece (2002) evaluated the start up performance of anaerobic digestion using two different sources of seed sludge. Anaerobic digester sludge (ADS) and aerobic waste activated sludge (WAS) were used as seed sludge for anaerobic digesters at mesophilic (35°C) and thermophilic (55°C) conditions. The study was conducted in two experiments. First, thermophilic anaerobic reactors were used to investigate start-up performance with a feed of calcium acetate and calcium propionate. The WAS seeded reactor started to produce $CH_4$ soon after acetate feeding without a lag time, while the ADS seeded reactor had a lag time of 10 days. The experiment was conducted without temperature acclimation for the thermophilic sludge. The results indicated that the WAS reactor had a significant capacity to biodegrade acetate anaerobically (Kim and Speece, 2002).

Kim and Speece (2002) also compared the methanogenic activity of anaerobic digestion seeded by the WAS and ADS. Both reactors were operated under mesophilic and thermophilic temperatures. The WAS seeded reactor produced more $CH_4$ per unit amount of seeded VSS than the ADS reactor. The WAS reactor performance was better than the ADS reactor at both mesophilic and thermophilic conditions. The WAS reactor at mesophilic temperature biodegraded propionate much faster than at thermophilic temperature. When acetate was used as the feed, the WAS reactor started producing $CH_4$ within five days at both mesophilic and thermophilic reactors. On the other hand, the mesophilic ADS reactor started

producing $CH_4$ very soon, i.e. within one day while the thermophilic ADS reactor started producing $CH_4$ very late, i.e. within 30 days (Kim and Speece, 2002).

The results showed the validity of WAS as a seed source for anaerobic digestion. The WAS reactor obtained much better performance than the ADS reactor at both mesophilic and thermophilic temperatures for both acetate and propionate degradations. Kim and Speece (2002) hypothesized that there might be anaerobic bacteria with high activity in the WAS. The other was that dominant bacteria in WAS might function in micro zones with anaerobic conditions and that methanogens and propionate degrading organism might be much more tolerant of aerobic conditions than previously thought.

# CHAPTER 3
# METHODOLOGY

This study was conducted to evaluate the performance of biological treatment for treating non-penicillin based pharmaceutical wastewater. The study was conducted in two phases; Phase I used two trains of reactors (semi-anaerobic-aerobic and aerobic), meanwhile Phase II used four anaerobic reactors. Phase I was performed as a preliminary study of pharmaceutical wastewater treatment. In this phase, an aerobic biomass from a sewage treatment plant was evaluated as seed biomass in biological process reactor. In Phase II, only anaerobic reactors seeded by using the same source of biomass as in Phase I were investigated. Figure 3.1 shows the schematic diagram of this study.

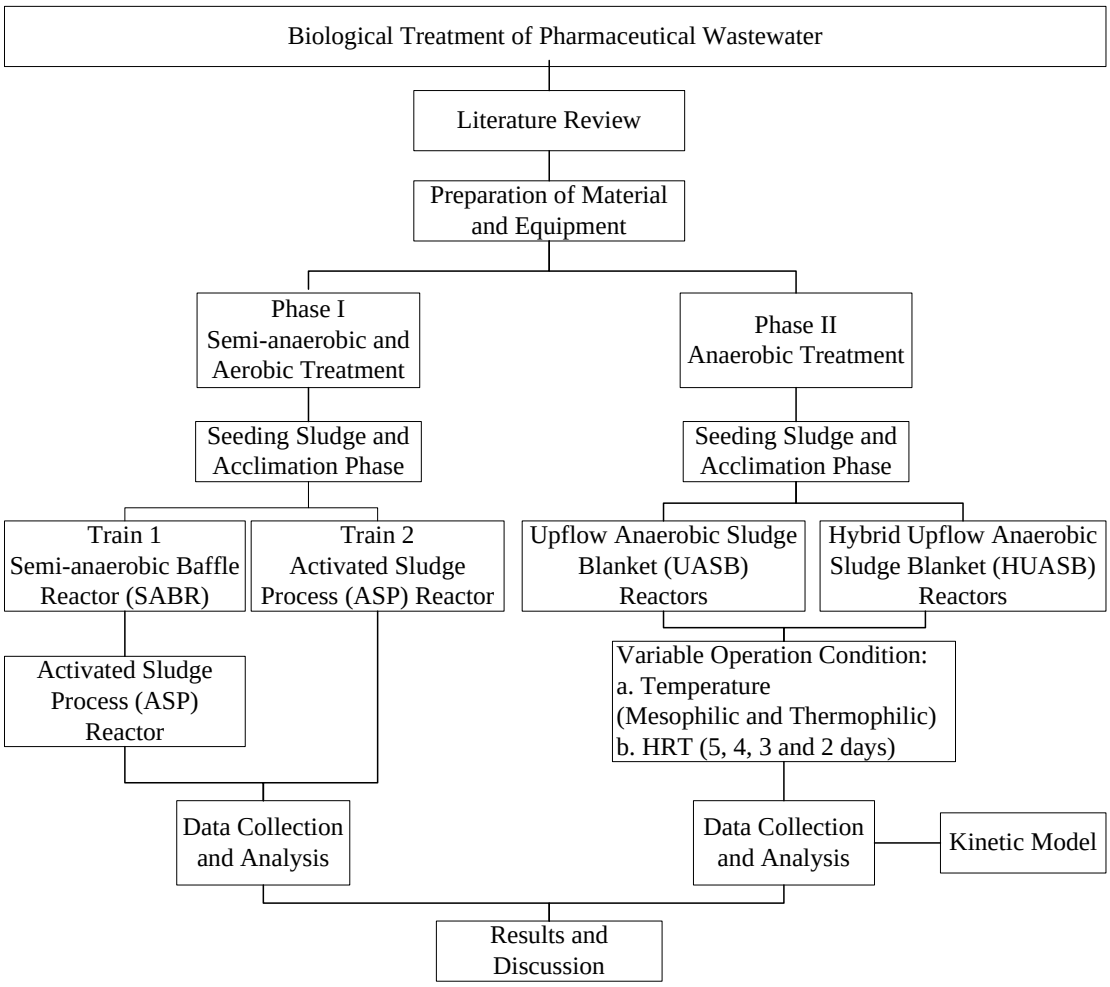


Figure 3.1 Schematic diagram of study

## 3.1 Phase I: Treatment of Pharmaceutical Wastewater Using Semi-anaerobic and Aerobic Reactors

### 3.1.1 Phase I Experimental Procedure

The biological treatment in this study consisted of two treatment trains; Train 1 which consisted of a semi-anaerobic reactor followed by an aerobic reactor while Train 2 consisted of only an aerobic reactor. A schematic diagram of the treatment trains used in this study is shown in Figure 3.2.

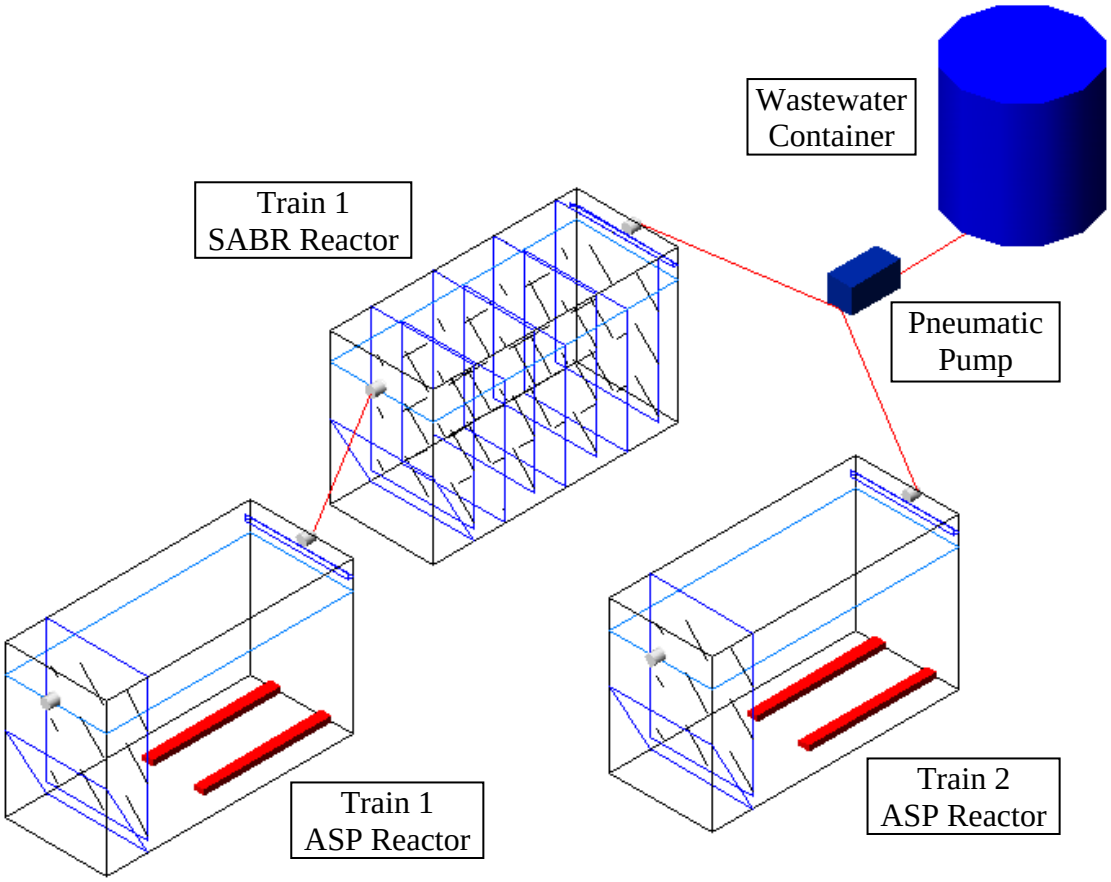


Figure 3.2 Phase I experimental diagram

### 3.1.2 Semi-anaerobic Baffle Reactor (SABR)

A laboratory-scale semi-anaerobic baffle reactor was used in Train 1. The acrylic reactor was fabricated with internal dimensions of 48 cm x 20 cm x 29 cm (L x B x H). The total volume was 27.8 L and the working volume was 23 L (liquid height of 24 cm). The reactor was operated as vertical flow and under ambient

temperature (27±3°C). The reactor consisted of seven baffle walls and without cover at the top. The Train 1 SABR used in this study is shown in Figure 3.3a.


Figure 3.3 (a) Train 1 SABR and (b) Train 1 ASP reactor

### 3.1.3 Activated Sludge Process (ASP) Reactor

Laboratory-scale activated sludge process (ASP) reactors were used in Train 1 and Train 2. The acrylic ASP reactors consisted of two sections: aeration and settling sections. The aeration section had internal dimensions of 40 cm x 20 cm x 29 cm (L x B x H). The total volume was 23.2 L and the working volume was 19.2 L (liquid height of 24 cm). The settling section had internal dimensions of 8 cm x 20 cm x 24 cm (L x B x H). The slope of settling section was 45°. The flow was introduced in the settling section at the bottom. Samples of the effluent were taken from the settling section. Diffuse aerators were used in the activated sludge reactors. The Train 1 ASP reactor and Train 2 ASP reactor used in this study are shown in Figure 3.3b and Figure 3.4, respectively.

### 3.1.4 Source of Wastewater

Pharmaceutical wastewater was collected from a non-penicillin based pharmaceutical factory in Seri Iskandar, Perak, Malaysia. Wastewater samples were collected every two or three weeks. The biological reactors were fed with the pharmaceutical wastewater without pre-treatment. The wastewater was stored in a cold room at 4°C before use. The characteristics of pharmaceutical wastewater during Phase I are shown in Table 3.1.

Figure 3.4 Train 2 ASP reactor

Table 3.1 Characteristic of pharmaceutical wastewater (Phase I)

| Parameter | Concentration (mg/L) |
|---|---|
| $BOD_5$ | 462-1299 |
| COD | 607-1953 |
| TSS | 7-38 |
| $NH_3$-N | 7.4-24.8 |
| $NO_3$-N | 0.3-0.8 |
| Total Phosphorus | 2.54-6.57 |
| pH | 5.17-6.65 |

### 3.1.5 Seed Biomass and Acclimatization Phase

The seed biomass for ASP reactors was taken from return activated sludge (RAS) of Universiti Teknologi PETRONAS's (UTP) Sewage Treatment Plant (STP), while the seed biomass for semi-anaerobic reactor was taken from sludge thickener. The semi-anaerobic reactor was inoculated with 8.5 L sludge and ASP reactors were inoculated with 10 L sludge. The seed biomass for semi-anaerobic reactor was taken from sludge thickener in order to obtain high sludge concentration. For initial acclimatization, all reactors were batch-fed daily with pharmaceutical wastewater for 7 days. After 7 days, both trains were continuously fed with pharmaceutical wastewater at a flow rate of 7.7 L/day.

## 3.2 Phase II: Treatment of Pharmaceutical Wastewater Using UASB and HUASB Reactors

### 3.2.1 Phase II Experimental Procedure

The experimental investigation was carried out utilising four reactors. Two reactors were UASB and two reactors were HUASB. The schematic diagrams of the four 5 L UASB and HUASB laboratory-scale reactors used in this study are shown in Figure 3.5 and Figure 3.6, respectively. One UASB and one HUASB were operated under mesophilic conditions (35±2°C) and the others were under thermophilic conditions (55±2°C). Temperatures were maintained by heating jackets that were connected to temperature control devices. Each temperature control device worked based on temperature inside the reactor, which was measured by a thermometer. Pharmaceutical wastewater was continuously fed to the reactors using a peristaltic pump (Master Flex, Cole Palmer). Four HRTs i.e. five, four, three and two days were used for all reactors during this study. A stirrer was used in feed tank to ensure a homogeneous wastewater influent.

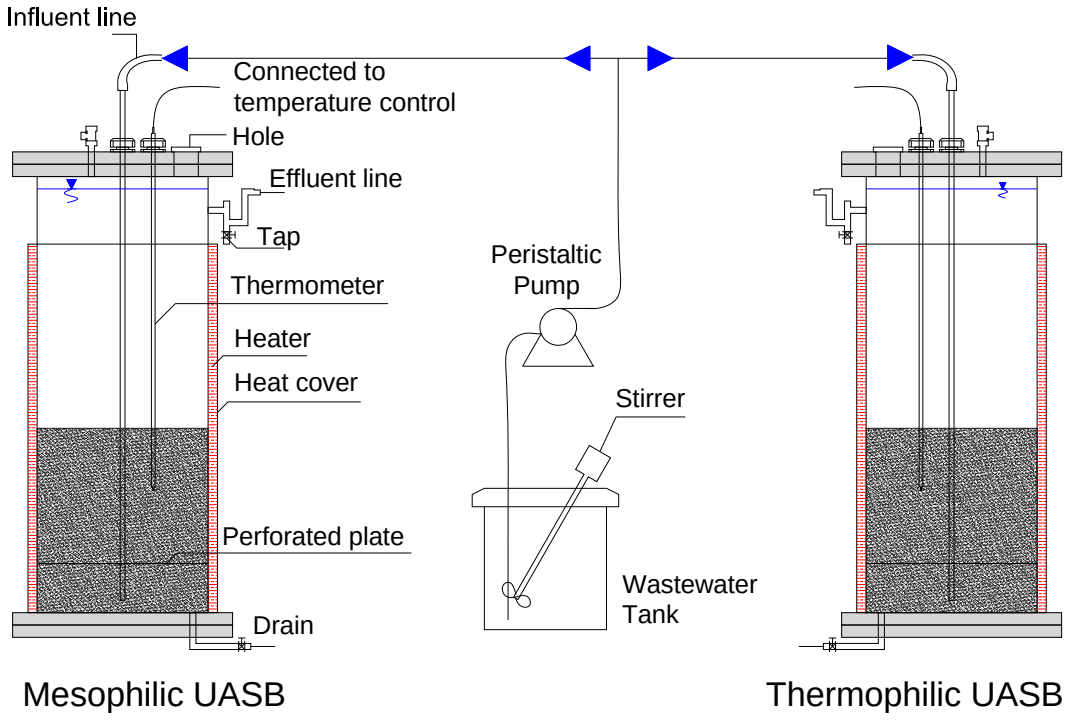


Figure 3.5 Phase II schematic diagram of UASB reactors

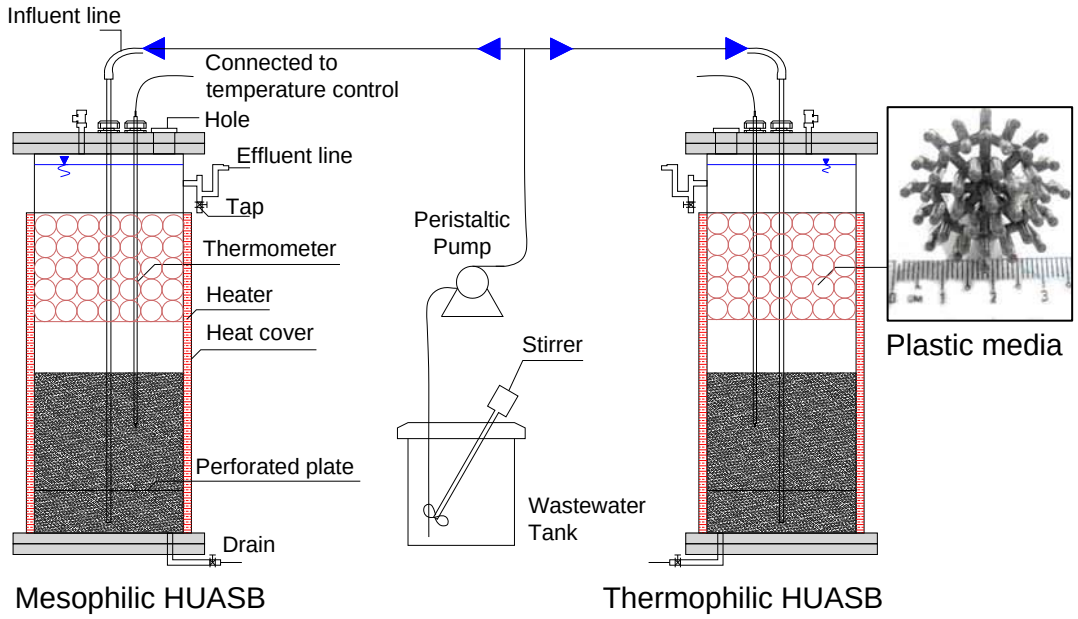


Figure 3.6 Phase II schematic diagram of HUASB reactors

### 3.2.2 UASB Reactors

The UASB reactors (Armfield Anaerobic Digester W8) with total liquid volume of 5 L (empty volume 5.5 L) were used throughout the study (Figure 3.7a). The UASB reactors were made from an acrylic column with 140 mm of diameter (internal) and 355 mm of height (330 mm water depth). A perforated plate of 3 mm thickness with perforations of 8 mm diameter was placed at the bottom of the column in order to ensure proper distribution of flow through the reactor. The wastewater entered at the centre of the UASB reactors and flowed upward through the perforated plate. Sludge sampling ports were provided at the bottom of each reactor. The UASB reactors had 2 cm clear gap above the outlet to separate the gas from the wastewater, so the empty volume of reactors was 5.5 L.

### 3.2.3 HUASB Reactors

The HUASB reactors had a UASB portion (3.75 L) under a fixed film portion (1.25 L) (Figure 3.7b). The HUASB reactors were UASB reactors (Armfiled Anaerobic Digester W8) with some modifications inside the column. Plastic balls of 25 mm diameter were used as fixed film media.

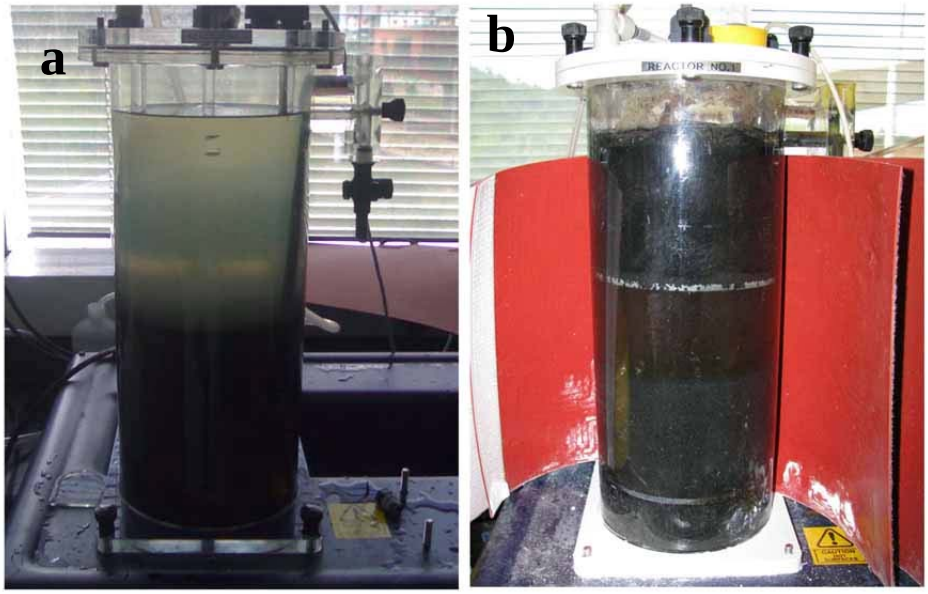


Figure 3.7 (a) UASB reactor and (b) HUASB reactor

### 3.2.4 Operation of the Reactors

The reactors were fed by pharmaceutical wastewater from a non-penicillin based product factory at Bangi, Malaysia without pre-treatment and dilution. Wastewater samples were collected every three to four weeks from a common sump by grab sampling. PVC containers were used to store wastewater in a cold room at 4°C before use. The stored wastewater was transferred to an influent tank daily for feed. The characteristics of the pharmaceutical wastewater are summarized in Table 3.2.

The UASB reactors were fed with low strength wastewater (COD 400-500 mg/L) for 75 days at HRTs of five and three days. From day 76 to day 170, it was then fed with high strength wastewater (COD 1773-2217 mg/L) at HRTs of five, four, three and two days.

The HUASB reactors were started 62 days after the UASB reactors. For the first 12 days of the operation of HUASB reactor, the reactors were fed with low strength wastewater at HRT of four days. On the day 13 of operation, the HUASB reactors were then fed with high strength wastewater at HRTs of five, four, three and two days.

Table 3.2 Characteristic of pharmaceutical wastewater (Phase II)

| Parameter | Concentration (mg/L) |
|---|---|
| $BOD_5$ | 299-1596 |
| COD | 458-2217 |
| TSS | 15-50 |
| $NH_3$-N | 2.5-29.3 |
| $NO_3$-N | 0.3-1.8 |
| TKN | 35.2-57.7 |
| Total Phosphorus | 4.8-19.4 |
| Alkalinity | 309-377 |
| pH | 4.76-6.04 |

### 3.2.5 Seed Biomass

The seed biomass was obtained from a sludge thickener of the activated sludge process based sewage treatment plant (STP) at the Universiti Teknologi PETRONAS (UTP), Malaysia. The TVSS concentrations after seeding were measured as 16277 mg/L and 17335 mg/L in UASB and HUASB reactors, respectively. Activated sludge was chosen to seed the UASB reactor because of the validity of such sludge as seed for anaerobic reactor (Kim and Speece, 2002).

The reactors were inoculated with 2.5 L of sludge. In order to acclimatize the sludge with pharmaceutical wastewater, the reactors were batch feed with 2.5 L of pharmaceutical wastewater (COD 400-500 mg/L) for 14 days and with continuous flow for 14 days. The acclimation period allows reduction of oxygen levels to prevent inhibition of anaerobic bacteria as well as for the bacteria population to adjust to the feed wastewater.

## 3.3 Analytical Methods

### 3.3.1 Measurement of pH

The pH was measured with a Hach pH meter (Model Sension 4) using Platinum Series pH Electrode (Model 51910). The pH meter was calibrated with pH 4.0, 7.0 and 10.0 buffers.

### 3.3.2 Measurement of Alkalinity

Alkalinity was measured by Standard Methods Section 2320 B Titration Method (APHA, 2005). The pH value of 4.5 is suggested as the equivalence points for the corresponding alkalinity concentrations. The alkalinity analysis was performed using a properly calibrated auto titration (Metrohm 702 SM Titrino) at room temperature.

### 3.3.3 Measurement of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand 5 days ($BOD_5$)

COD was measured by the reactor digestion method (Method 8000) using Hach reagent kit (Hach, 2002). High range COD digestion reagent vials were used for this purpose. Colorimetric determination of COD was carried out at 620 nm using a Hach spectrophotometer DR 2000. $BOD_5$ was measured by Standard Methods Section 5210 B 5 Day BOD Test (APHA, 2005). Dissolved oxygen (DO) was measured using a YSI 5100 Dissolved Oxygen Meter.

### 3.3.4 Measurement of Total Suspended Solids (TSS) and Total Volatile Suspended Solids (TVSS)

TSS was determined according to the Standard Methods Section 2540 D Total Suspended Solids Dried at 103-105°C Method (APHA, 2005). For TVSS measurement, the residue from the TSS measurements was ignited to constant weight at 550°C in the muffle furnace (Nabertherm L15/12/P320) according to Standard Methods Section 2540 E Fixed and Volatile Solids Ignited at 550°C Method (APHA, 2005). Mixed Liquor Suspended Solids (MLSS) was measured by TSS

method and Mixed Liquor Volatile Suspended Solids (MLVSS) was measured by TVSS method with proper dilution.

### 3.3.5 Measurement of Ammonia Nitrogen ($NH_3$-N), Nitrate Nitrogen ($NO_3$-N) and Total Phosphorus (TP)

$NH_3$-N was measured by Nessler Method (Method 8038), $NO_3$-N by Cadmium Reduction Method (Medium Range) using Hach Powder Pillow and TP by PhosVer 3 (Ascorbic Acid) Method using Hach Powder Pillow (Hach, 2002).

### 3.3.6 Measurement of Total Kjeldahl Nitrogen (TKN)

The macro-kjeldahl method was applied to measure TKN according to Standard Methods Section 4500-$N_{org}$ B Macro-Kjeldahl Method (APHA, 2005). For digestion, Buchi K-424 Digestion Unit and Buchi B-414 Scrubber Unit were used, whereas for distillation, Buchi K-314 Distillation Unit was used. Selenium catalyst tablets were used in TKN measurement. For ammonia nitrogen measurement, Standard Methods Section 4500 C Titrimetric Method (APHA, 2005) was used. Titration was performed using a properly calibrated auto titration (Metrohm 702 SM Titrino) at room temperature.

### 3.3.7 Measurement of Volatile Fatty Acids (VFA)

VFA was measured by esterification method (Method 8196) using a DR 2000 spectrophotometer (Hach, 2002). The sample was centrifuged by Heraeus Biofuge Primo before it was analyzed. All volatile acids present are reported as their equivalent mg/L as acetic acid (HOAC).

### 3.3.8 Measurement of Methane Gas Production

Methane production was monitored by liquid displacement. The top of each reactor was connected to a gas tank for gas collection. The displacement liquid was a 5% NaOH solution with thymol blue as indicator. NaOH was chosen because it absorbs $CO_2$ and allows $CH_4$ to pass through it. The blue colour of indicator will be discharged when the $CO_2$ absorption capacity of the solution is exhausted

(Isa et al., 1993; Leitao, 2004). However, the methane production data was not included in the results and discussion because there appeared to be some faults with the gas collection system. The methane production was only about 50% of the theoretical values based on stoichiometry calculation (350 mL $CH_4$/g COD).

### 3.4 Data Analysis

Statistical analysis, analysis of variance (ANOVA) was applied to the data obtained from the different reactors and in different operation condition in order to assess cause distinct effects on the performance of the reactors. One-way and two-way ANOVA were used to determine the significant difference between data that were obtained from each variable of the experiments.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 Phase I Results: Treatment of Pharmaceutical Wastewater using Semi-anaerobic and Aerobic Reactors

The Phase I study was conducted to observe the performance of semi-anaerobic and aerobic system treating non-penicillin pharmaceutical wastewater. The study was performed using a semi-anaerobic baffled reactor (SABR) and two activated sludge process (ASP) reactors. The reactors were divided into two trains; Train 1 (SABR-ASP reactor) and Train 2 (ASP reactor). The performance of each reactor was evaluated in terms of COD and $BOD_5$ removal efficiencies. The nutrients and biomass in the reactors were also monitored.

### 4.1.1 COD and $BOD_5$ in Semi-anaerobic and Aerobic Reactors

The COD removal and COD concentration in Phase I are shown in Figure 4.1 and Figure 4.2, respectively and the overall COD removal in Train 1 and Train 2 is shown in Figure 4.3. For the first ten days, the influent COD concentration varied from 1853 to 1953 mg/L. The COD removal ranged from 86 to 93% and the effluent COD concentration varied from 142 to 265 mg/L in SABR. The Train 1 ASP reactor that received wastewater from the SABR achieved COD removal of 33-82%. Furthermore, the overall COD removals ranged from 95 to 98% and 81 to 89% for Train 1 and Train 2, respectively. The final COD concentrations varied from 45 to 96 mg/L and 207 to 364 mg/L for Train 1 and Train 2, respectively.

From day 11 to day 28, the influent COD concentration varied from 791 to 987 mg/L. The COD removal ranged from 71 to 92% and the effluent COD concentration varied from 70 to 246 mg/L in SABR. The Train 1 ASP reactor achieved a COD removal of 31-72%. The overall COD removals ranged from 90 to 94% and 85 to 92% for Train 1 and Train 2, respectively. The final COD concentrations varied from 48 to 102 mg/L and 66 to 140 mg/L for Train 1 and Train 2, respectively.

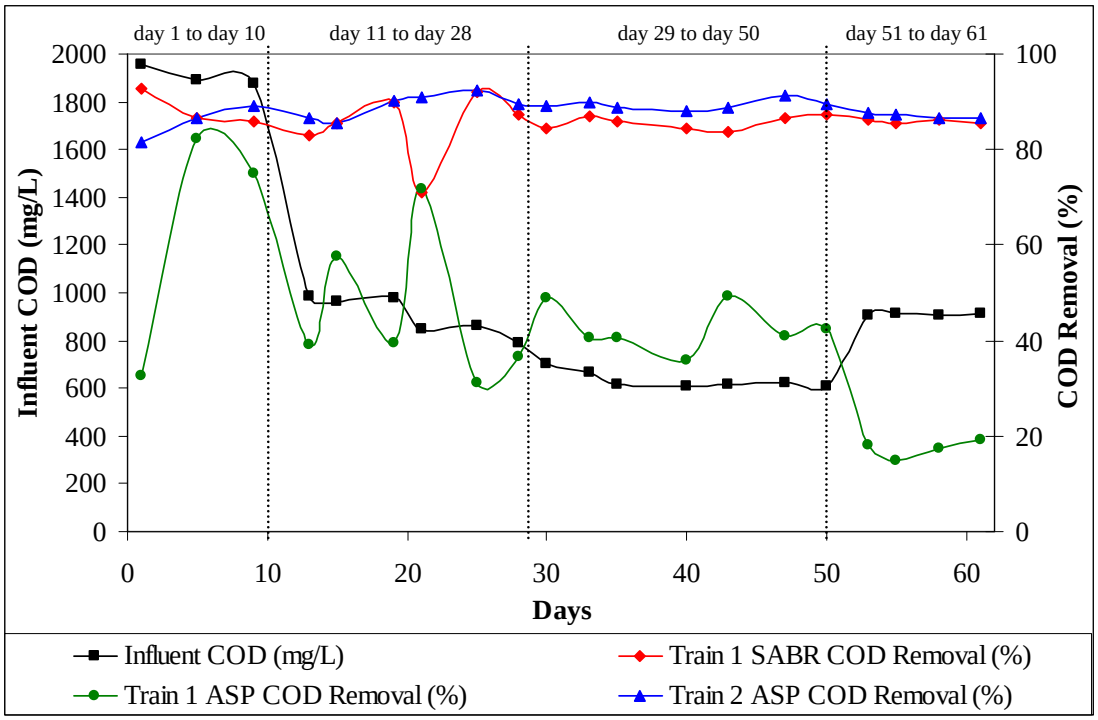


Figure 4.1 Phase I influent COD concentration and COD removal in the reactors

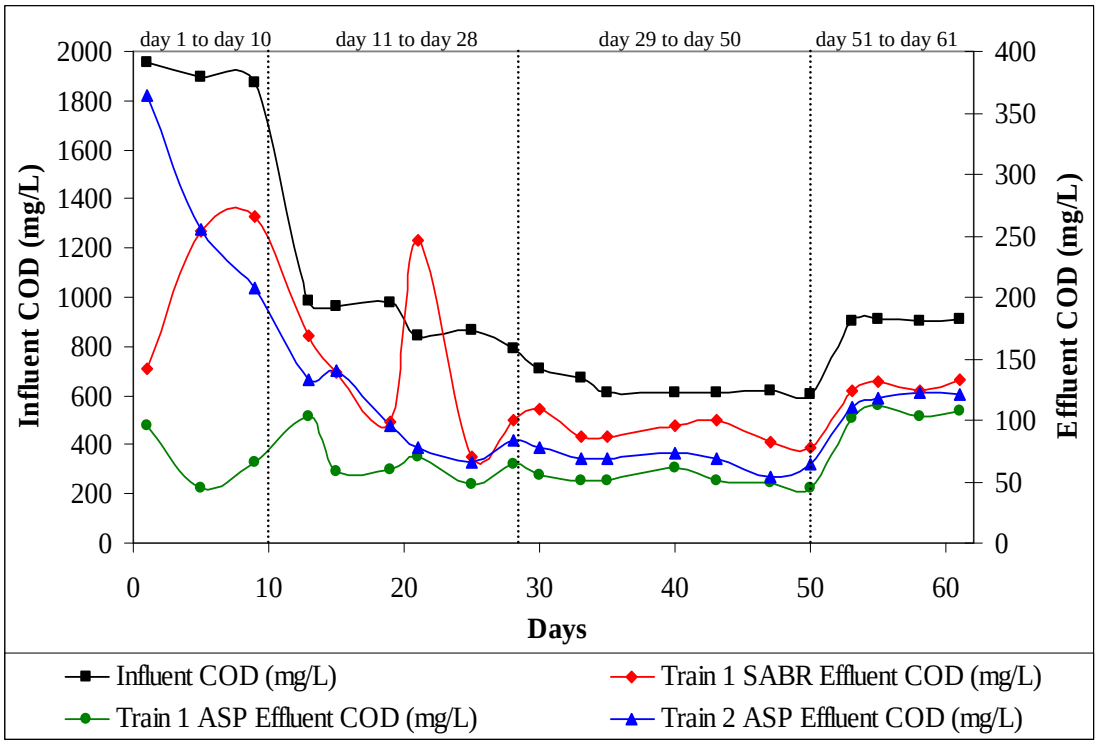


Figure 4.2 Phase I influent and effluent COD concentrations in the reactors

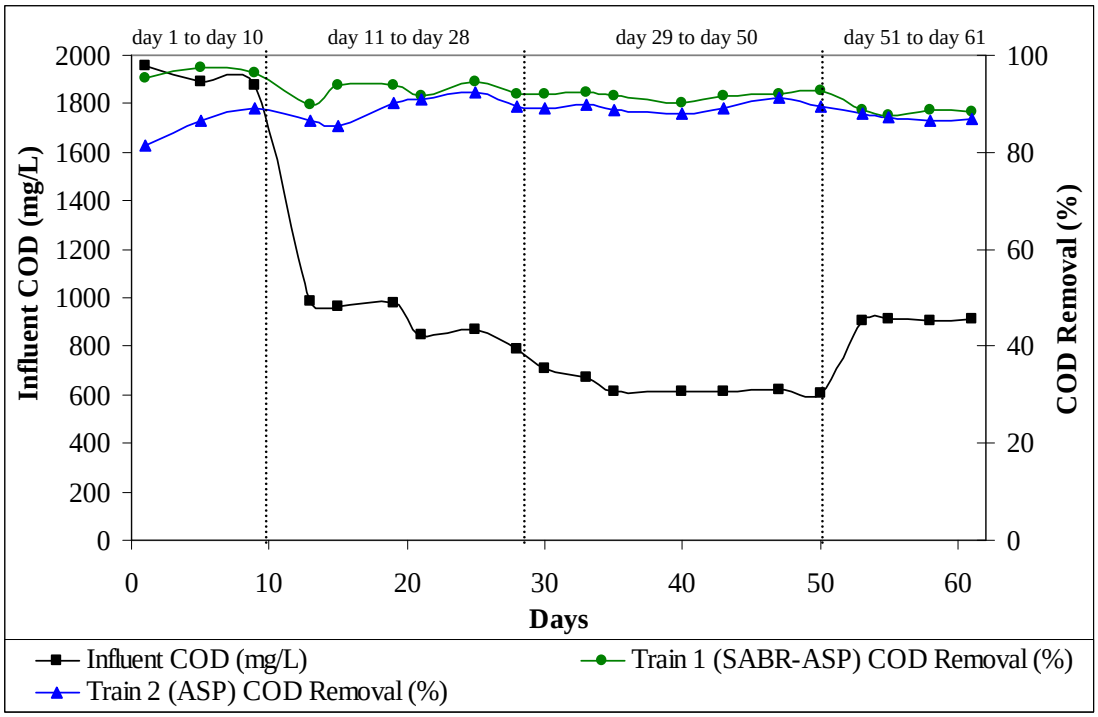


Figure 4.3 Influent COD concentration and Train 1 and Train 2 COD removal

From day 29 to day 50, the influent COD concentration ranged from 607 to 706 mg/L. The COD removal ranged from 84 to 87% in SABR, whereas the effluent COD concentration varied from 77 to 109 mg/L. The Train 1 ASP reactor achieved a COD removal of 36-49%. Furthermore, the overall COD removals ranged from 90 to 93% and 88 to 91% for Train 1 and Train 2, respectively. The final COD concentrations varied from 45 to 61 mg/L and 54 to 77 mg/L for Train 1 and Train 2, respectively.

For the last 11 days, the influent COD concentration varied from 905 to 913 mg/L. The COD removal ranged from 85 to 86% and the effluent COD concentration varied from 124 to 133 mg/L in SABR. The Train 1 ASP reactor achieved a COD removal of 15-19%. The overall COD removals ranged from 88 to 89% and 87 to 88% for Train 1 and Train 2, respectively. The final COD concentrations varied from 102 to 112 mg/L and 110 to 122 mg/L for Train 1 and Train 2, respectively.

The performance of each reactor was also evaluated in terms of the $BOD_5$ concentration. The $BOD_5$ removal and $BOD_5$ concentration in Phase I are shown in Figure 4.4 and Figure 4.5, respectively and the overall $BOD_5$ removal in Train 1 and Train 2 is shown in Figure 4.6. For the first ten days, the average influent $BOD_5$ concentration was 1299 mg/L. The average $BOD_5$ removal was 83% and the average effluent $BOD_5$ concentration was 225 mg/L in SABR. The Train 1 ASP reactor that received wastewater from the SABR achieved an average $BOD_5$ removal of 85%. Furthermore, the overall $BOD_5$ removals were 97% and 83% for Train 1 and Train 2, respectively. The final $BOD_5$ concentrations were 34 mg/L and 226 mg/L for Train 1 and Train 2, respectively. From day 11 to day 28, the influent $BOD_5$ concentration varied from 588 to 717 mg/L. The $BOD_5$ removal ranged from 66 to 85% and the effluent $BOD_5$ concentration varied from 70 to 246 mg/L in SABR. The Train 1 ASP reactor achieved a $BOD_5$ removal of 66-85%. The overall $BOD_5$ removals ranged from 89 to 92% and 84 to 89% for Train 1 and Train 2, respectively. The final $BOD_5$ concentrations varied from 48 to 77 mg/L and 69 to 118 mg/L for Train 1 and Train 2, respectively.

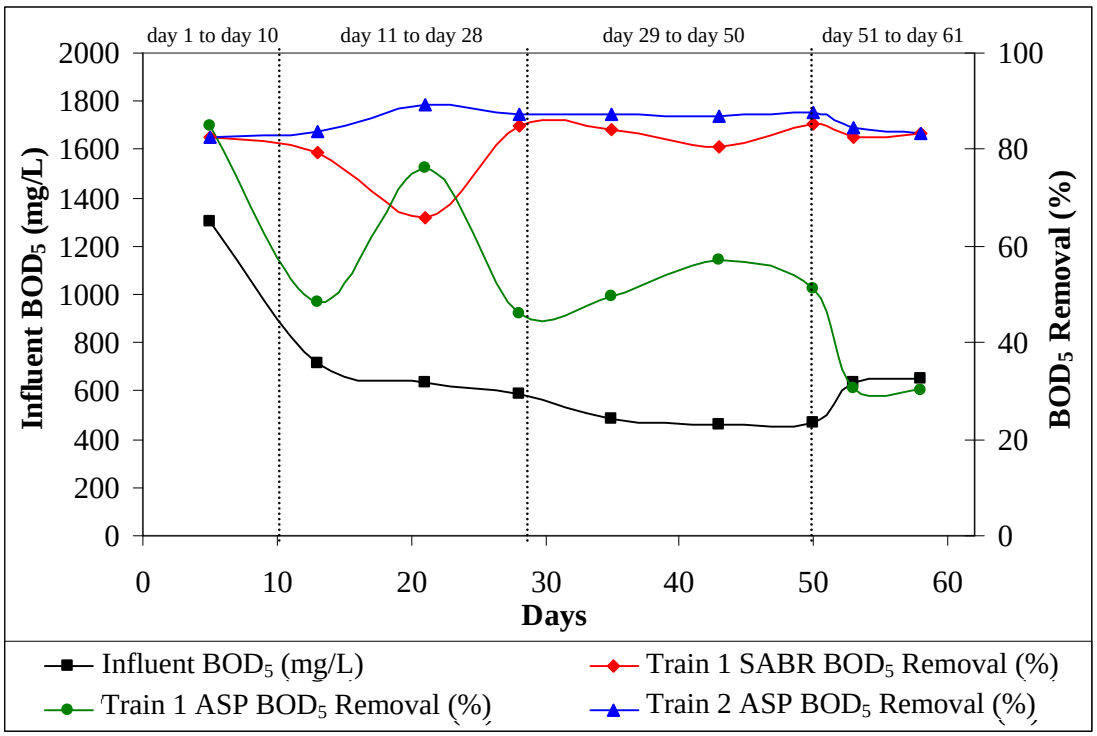


Figure 4.4 Phase I Influent $BOD_5$ concentration and $BOD_5$ removal in the reactors

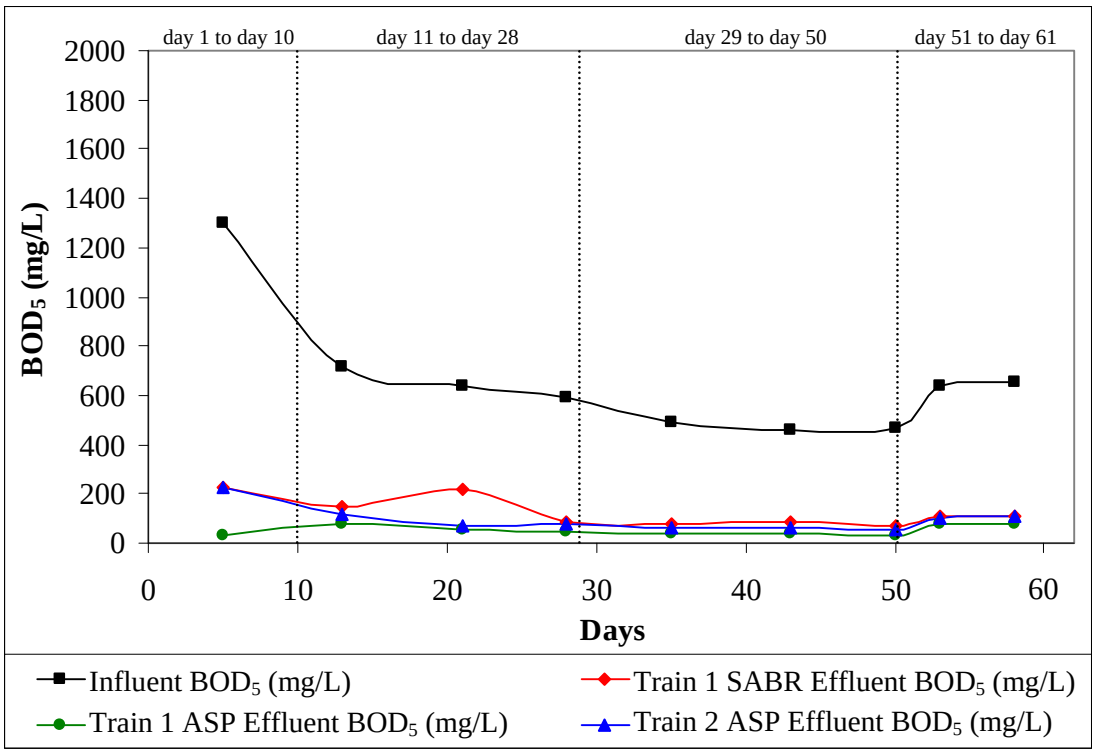


Figure 4.5 Phase I influent and effluent $BOD_5$ concentrations in the reactors

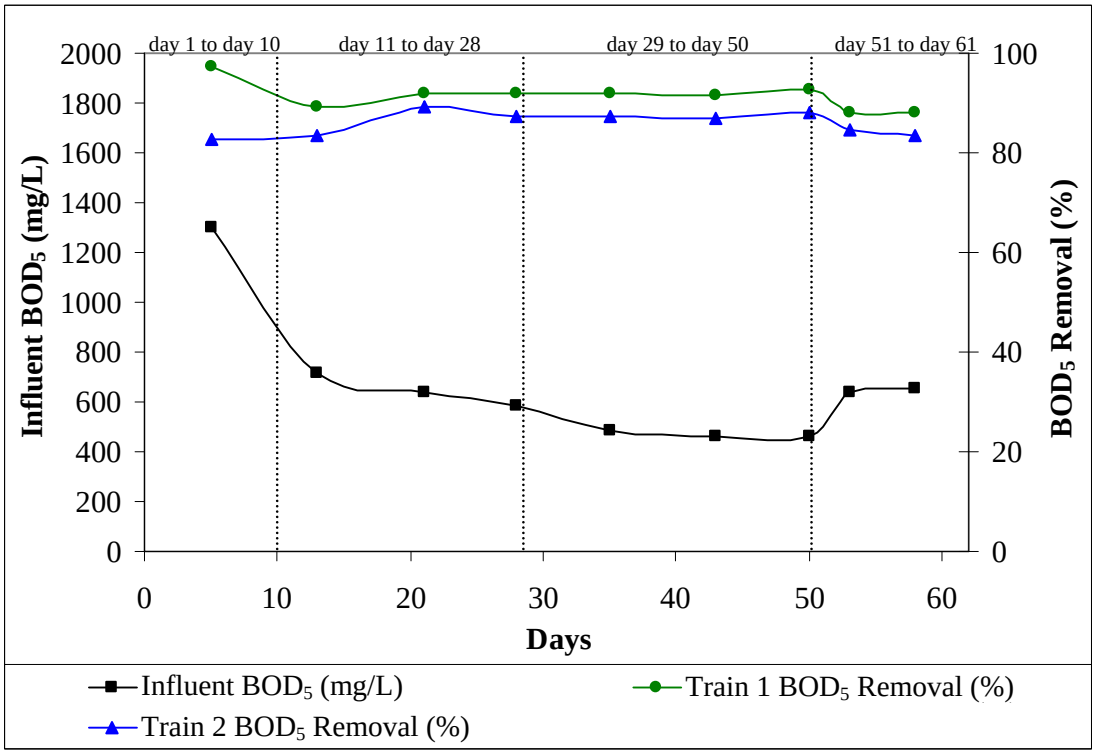


Figure 4.6 $BOD_5$ removal in Train 1 and Train 2

From day 29 to day 50, the influent $BOD_5$ concentration varied from 462 to 487 mg/L. The $BOD_5$ removal ranged from 81 to 85% and the effluent $BOD_5$ concentration varied from 69 to 89 mg/L in SABR. The Train 1 ASP achieved a $BOD_5$ removal of 50-57%. Furthermore, the overall $BOD_5$ removals ranged from 92 to 93% and 87 to 88% for Train 1 and Train 2, respectively. The final $BOD_5$ concentrations varied from 33 to 39 mg/L and 56 to 61 mg/L for Train 1 and Train 2, respectively.

For the last 11 days, the average influent $BOD_5$ concentration was 645 mg/L. The average $BOD_5$ removal was 83% and the average effluent $BOD_5$ concentration was 88 mg/L in SABR. The Train 1 ASP reactor achieved average $BOD_5$ removal of 30%. The average $BOD_5$ removals were 88% and 84% for Train 1 and Train 2, respectively. The average final $BOD_5$ concentrations were 77 mg/L and 103 mg/L for Train 1 and Train 2, respectively.

### 4.1.2 Total Suspended Solids (TSS) Analysis

In the 61 days, the reactors were fed with influent TSS concentration of 7-38 mg/L. The influent and effluent TSS concentrations during Phase I are shown in Figure 4.7. The effluent TSS concentration in SABR ranged from 18 to 58 mg/L while effluent TSS concentrations of 12-31 mg/L and 17-31 mg/L were found in Train 1 ASP reactor and Train 2 ASP reactor, respectively. The TSS concentrations increased because the settling sections of the reactors were not enough to settle the TSS. However, the effluent TSS concentrations in both ASP rectors were still low (less than 50 mg/L)

### 4.1.3 Mixed Liquor Suspended Solid (MLSS) and Sludge Retention Time (SRT)

In the acclimatisation period, approximately 0.5 L of mixed liquor was wasted daily to maintain a MLSS of 2000-4000 mg/L. Based on calculation, the SRT was approximately 38.4 days. During the 61 days, the MLSS concentration in Train 1 ASP reactor was lower than in Train 2 ASP reactor. Figure 4.8 shows the profile of

MLSS concentration and SRT during this study. In Train 1, the MLSS concentration varied from 2000 to 4367 mg/L while in Train 2, the MLSS concentration varied from 3083 to 5250 mg/L. The actual SRT varied from 32.35 to 36.81 days and 33.36 to 36.45 days for Train 1 ASP reactor and Train 2 ASP reactor, respectively.

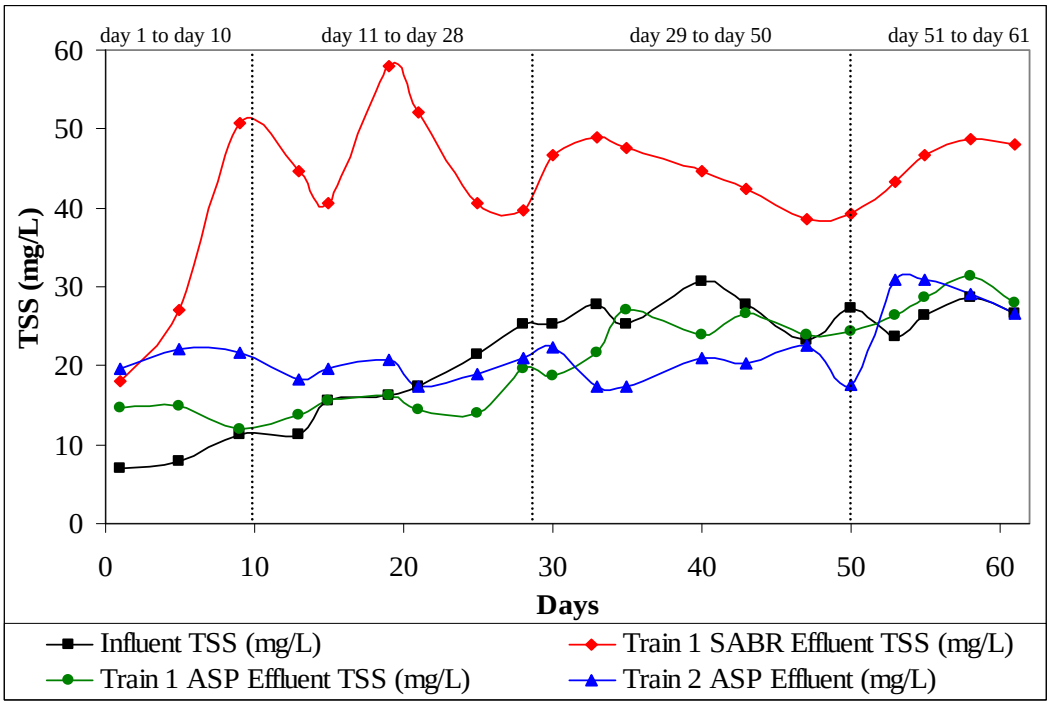


Figure 4.7 Phase I influent and effluent TSS concentrations in the reactors

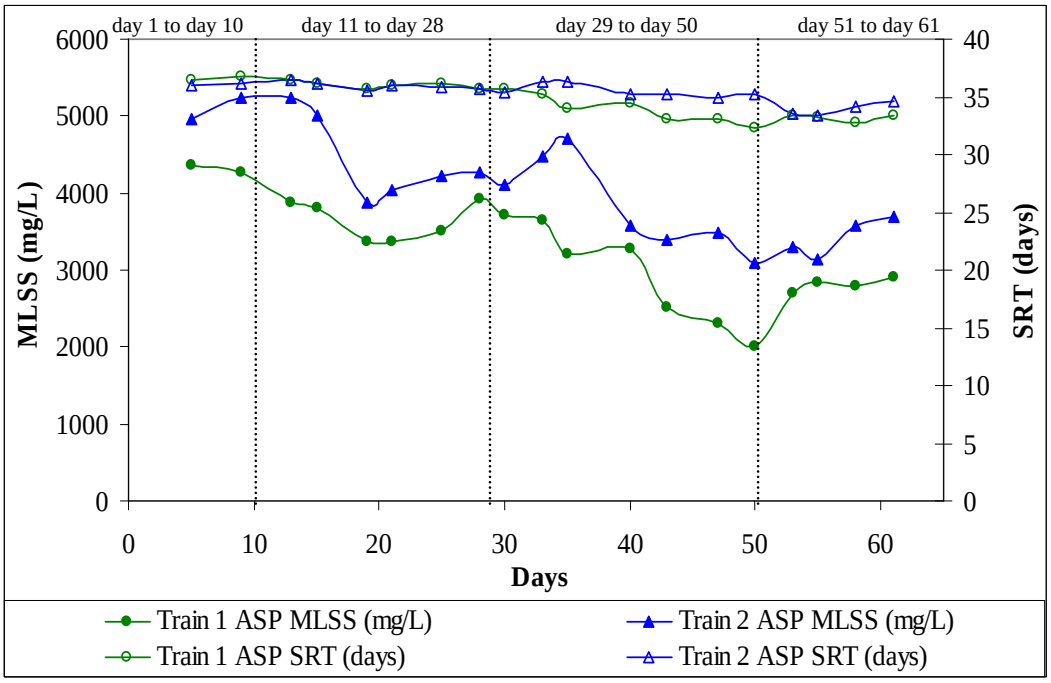


Figure 4.8 Phase I MLSS concentration and SRT in ASP reactors

### 4.1.4 Mixed Liquor Volatile Suspended Solid (MLVSS) and Food to Microorganism Ratio (F/M Ratio)

In the 61 days, the Train 1 ASP reactor was fed with influent $BOD_5$ of 69-225 mg/L while the Train 2 ASP reactor was fed with influent $BOD_5$ of 462-1299 mg/L. The MLVSS in ASP reactors ranged from 1100 to 2517 mg/L and 1850 to 3567 mg/L for Train 1 and Train 2, respectively. Based on calculations, the F/M ratios in ASP reactors ranged from 0.02 to 0.05 g $BOD_5$/g MLVSS and 0.07 to 0.19 g $BOD_5$/g MLVSS for Train 1 and Train 2, respectively. The F/M ratio of Train 1 ASP reactor was lower than the F/M ratio of the Train 2 ASP reactor because former received partially treated wastewater from the SABR. The lower F/M ratio also resulted in the lower concentration of biomass in Train 1 ASP reactor. The MLVSS concentrations varied in accordance with the organic content of the pharmaceutical wastewater. The MLVSS concentrations and F/M ratios in ASP reactors during the Phase I study are shown in Figure 4.9.

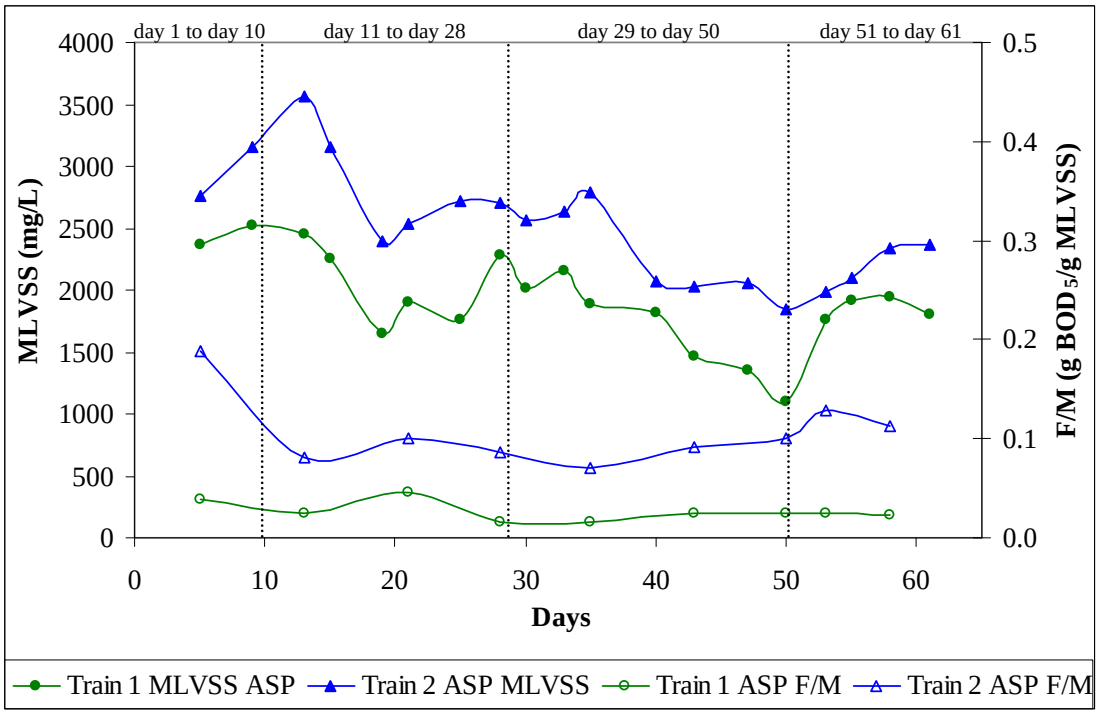


Figure 4.9 Phase I MLVSS concentration and F/M ratio in ASP reactors

### 4.1.5 Nutrients Analysis

Figure 4.10 to Figure 4.14 show the influent and effluent nutrient concentrations ($NH_3$-N, $NO_3$-N and TP) in Phase I. For the first ten days, the influent $NH_3$-N concentration ranged from 22.6 to 24.8 mg/L. The $NH_3$-N removal ranged from 46 to 52% and the effluent $NH_3$-N concentration varied from 11.4 to 13.4 mg/L in SABR. The Train 1 ASP reactor that received wastewater from the SABR achieved a $NH_3$-N removal of 69-74%. Furthermore, the overall $NH_3$-N removals ranged from 85 to 86% and 78 to 80% for Train 1 and Train 2, respectively. The final $NH_3$-N concentrations ranged from 3.2 to 3.5 mg/L and 4.65 to 5.32 mg/L for Train 1 and Train 2, respectively. The influent TP concentration ranged from 3.03 to 3.63 mg/L. The TP concentrations in SABR slightly decreased with effluent TP of 1.66-2.98 mg/L. The Train 1 ASP reactor that received wastewater from the SABR achieved the TP removal of 36-49%. The overall TP removals ranged from 49 to 65% and 36 to 46% for Train 1 and Train 2, respectively. The final TP concentrations ranged from 1.07 to 1.86 mg/L and 1.78 to 1.97 mg/L for Train 1 and Train 2, respectively.

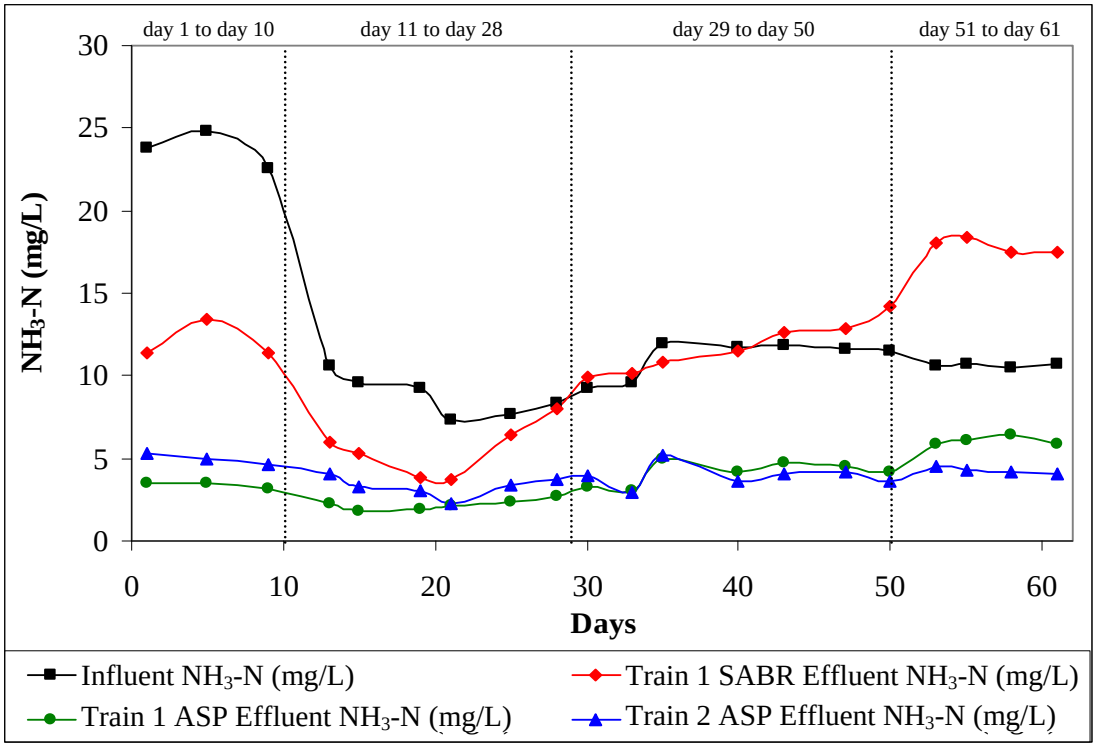


Figure 4.10 Phase I influent and effluent $NH_3$-N concentrations in the reactors

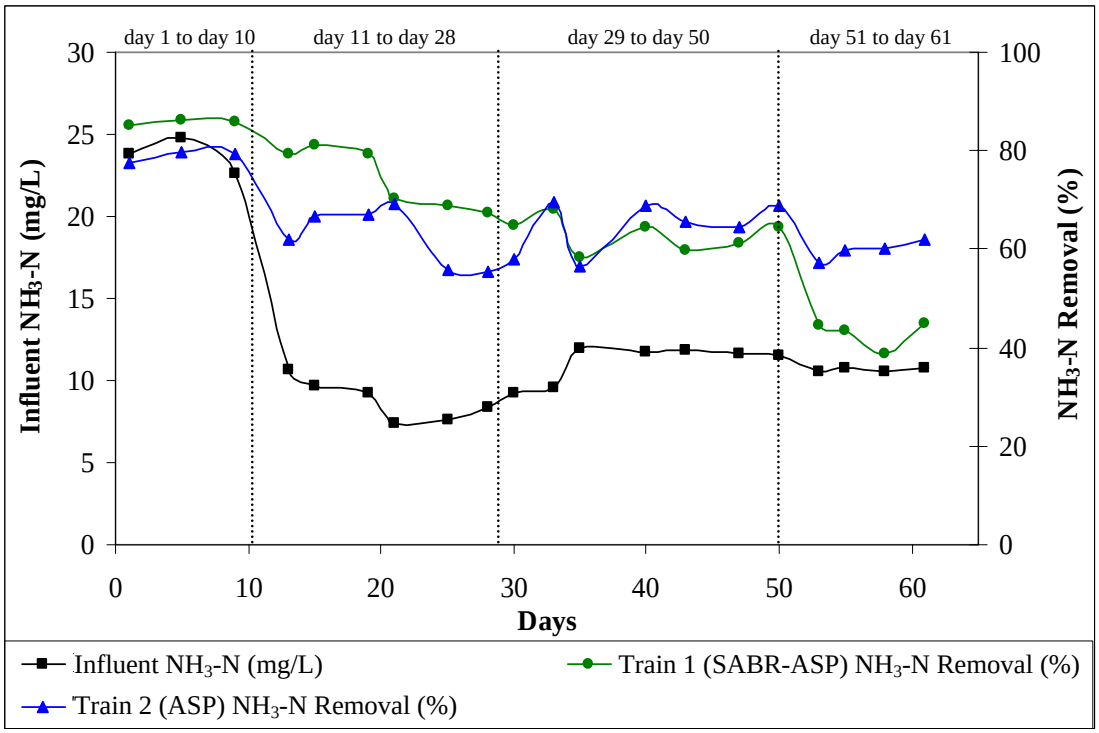


Figure 4.11 Influent $NH_3$-N concentration and $NH_3$-N removal in Train 1 and Train 2

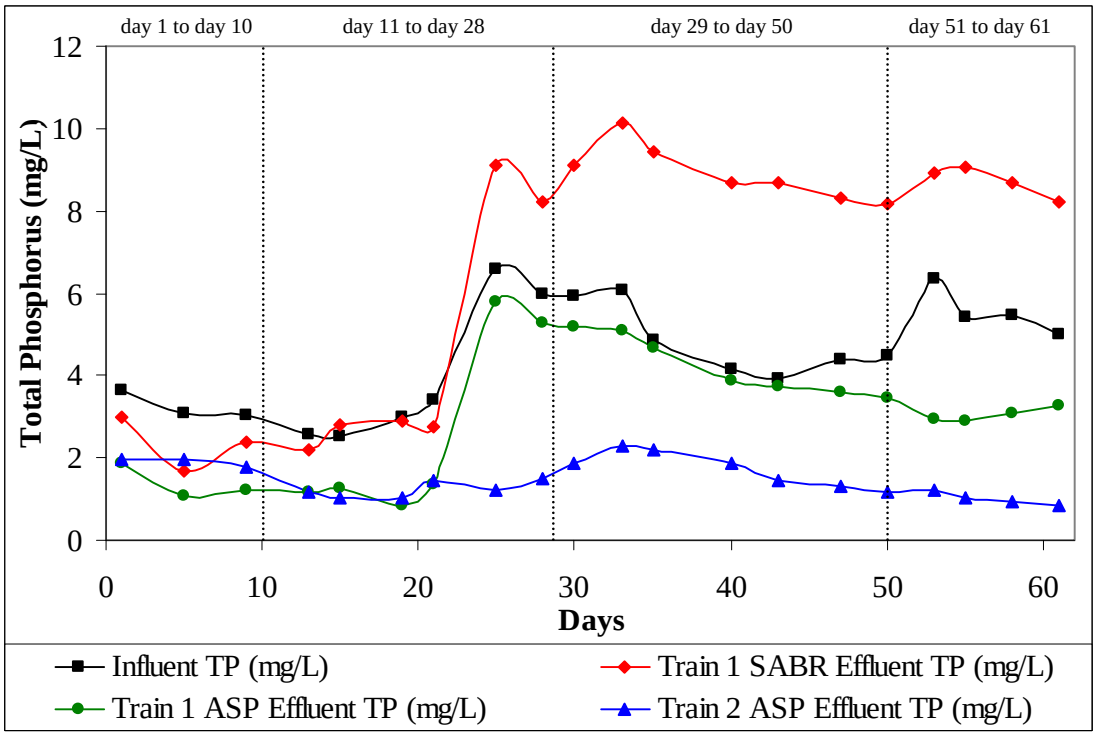


Figure 4.12 Phase I influent and effluent TP concentrations

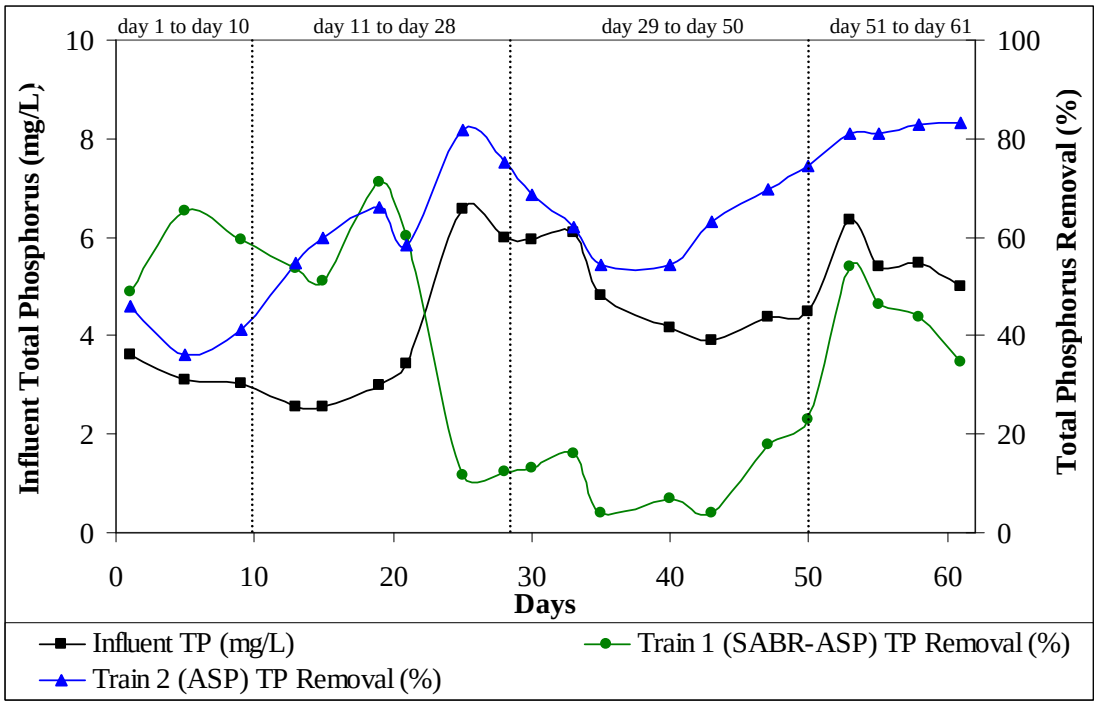


Figure 4.13 Influent TP concentration and TP removal in Train 1 and Train 2

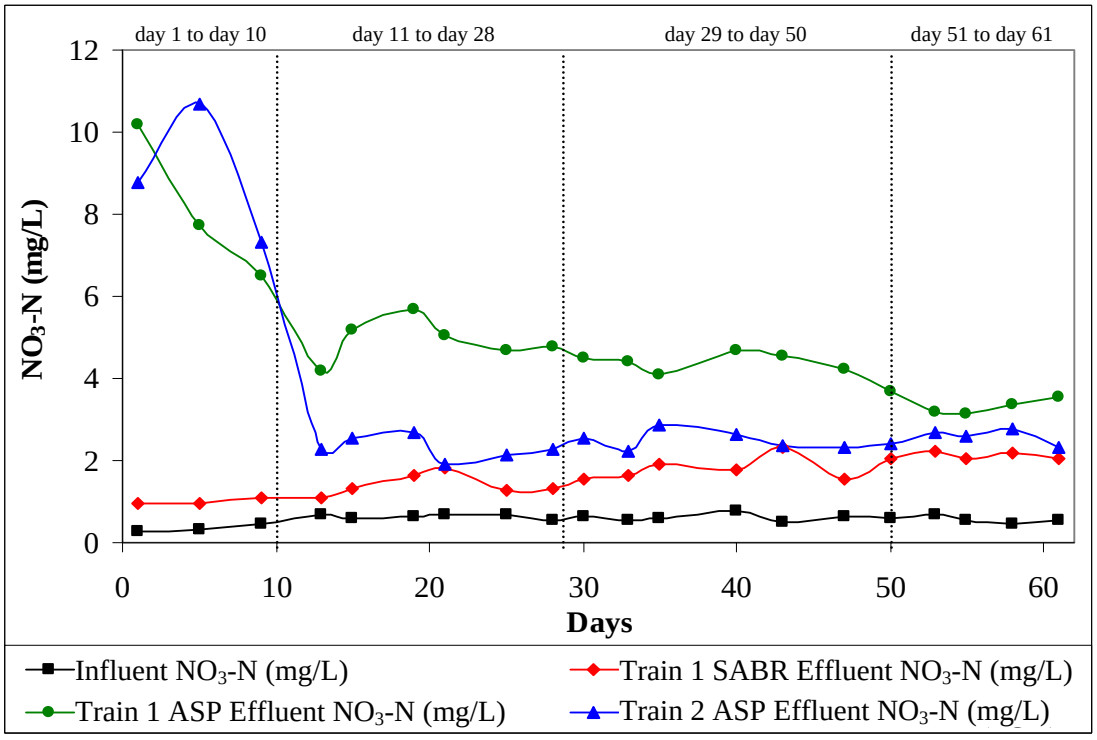


Figure 4.14 Phase I influent and effluent $NO_3$-N concentrations in the reactors

From day 11 to day 28, the influent $NH_3$-N concentration was lower than the influent at the first ten days. The influent $NH_3$-N concentration ranged from 7.4 to 10.6 mg/L. The $NH_3$-N removal ranged from 3 to 59% and the effluent $NH_3$-N concentration varied from 3.7 to 8.0 mg/L in SABR. The Train 1 ASP reactor achieved the $NH_3$-N removal of 42-66%. The overall $NH_3$-N removals ranged from 68 to 81% and 55 to 69% for Train 1 and Train 2, respectively. The final $NH_3$-N concentrations ranged from 1.80 to 2.70 mg/L and 2.27 to 4.02 mg/L for Train 1 and Train 2, respectively. The influent TP concentration ranged from 2.54 to 6.57 mg/L. The TP concentrations in SABR slightly increased with effluent TP of 2.18-9.10 mg/L. The Train 1 ASP reactor achieved the TP removal of 36-70%. Furthermore, the overall TP removals ranged from 12 to 72% and 55 to 82% for Train 1 and Train 2, respectively. The final TP concentrations ranged from 0.86 to 5.81 mg/L and 1.02 to 1.50 mg/L for Train 1 and Train 2, respectively.

From day 29 to day 50, the influent $NH_3$-N concentration was similar with the influent at the last eleven days. From day 29 to day 50, the influent $NH_3$-N concentrations ranged from 9.3 to 11.9 mg/L whereas at the last eleven days, the influent $NH_3$-N concentration ranged from 10.5 to 10.8 mg/L. The $NH_3$-N concentration at SABR increased and the effluent $NH_3$-N concentration varied from 9.9 to 18.4 mg/L. The Train 1 ASP reactor achieved a $NH_3$-N removal of 54-71%. Furthermore, the overall $NH_3$-N removals ranged from 59 to 68% and 56 to 69% for Train 1 and Train 2, respectively. The final $NH_3$-N concentrations ranged from 3.07 to 6.43 mg/L and 2.93 to 5.20 mg/L for Train 1 and Train 2, respectively. From day 29 to day 50, the influent TP concentration ranged from 3.90 to 6.08 mg/L whereas it ranged from 5.00 to 6.33 mg/L for the last eleven days. The TP concentration at SABR increased and the effluent TP concentration varied from 8.17 to 10.12 mg/L. The Train 1 ASP reactor achieved a TP removal of 43-68%. The overall TP removals ranged from 4 to 54% and 55 to 83% were for Train 1 and Train 2, respectively. The final TP concentrations ranged from 2.90 to 5.16 mg/L and 0.84 to 2.31 mg/L for Train 1 and Train 2, respectively.

Under anaerobic conditions, phosphorus accumulating organisms (PAOs) will assimilate fermentation products (e.g. volatile fatty acids) into storage products within the cells with concomitant release of phosphorus from storage polyphosphates. Under aerobic conditions, energy is produced by the oxidation of storage products and polyphosphate storage within the cell increases (Metcalf & Eddy, 2003).

The average influent $NO_3$-N concentration ranged from 0.3 to 0.8 mg/L. The result from all reactors showed that the $NO_3$-N concentrations increased. The effluent $NO_3$-N concentration in SABR varied from 0.9 to 2.3 mg/L. The final $NO_3$-N concentrations ranged from 3.1 to 10.2 mg/L and 1.9 to 10.7 mg/L for Train 1 and Train 2, respectively. For the last 30 days, the effluent $NH_3$-N concentration increased and the effluent $NO_3$-N concentration was constant in SABR because nitrification did not occur.

## 4.2 Phase II Results: Treatment of Pharmaceutical Wastewater Using UASB and HUASB Reactors

In Phase II study, biological treatments were evaluated to treat non-penicillin pharmaceutical wastewater using UASB and HUASB reactors under mesophilic (35±2°C) and thermophilic (55±2°C) conditions. The reactors were fed with low strength and high strength influent at HRTs of five, four, three and two days. The performance of each reactor was evaluated in terms of COD and $BOD_5$ removals. The nutrients, VFA, alkalinity and pH in the reactors were also monitored.

### 4.2.1 COD and $BOD_5$ in Mesophilic and Thermophilic UASB Reactors

In the first 13 days, the reactors were fed with influent COD concentration of 458-499 mg/L at HRT of five days. The COD concentration in UASB reactors during this study is shown in Figure 4.15 and the UASB reactors performance in this study is shown in Figure 4.16.

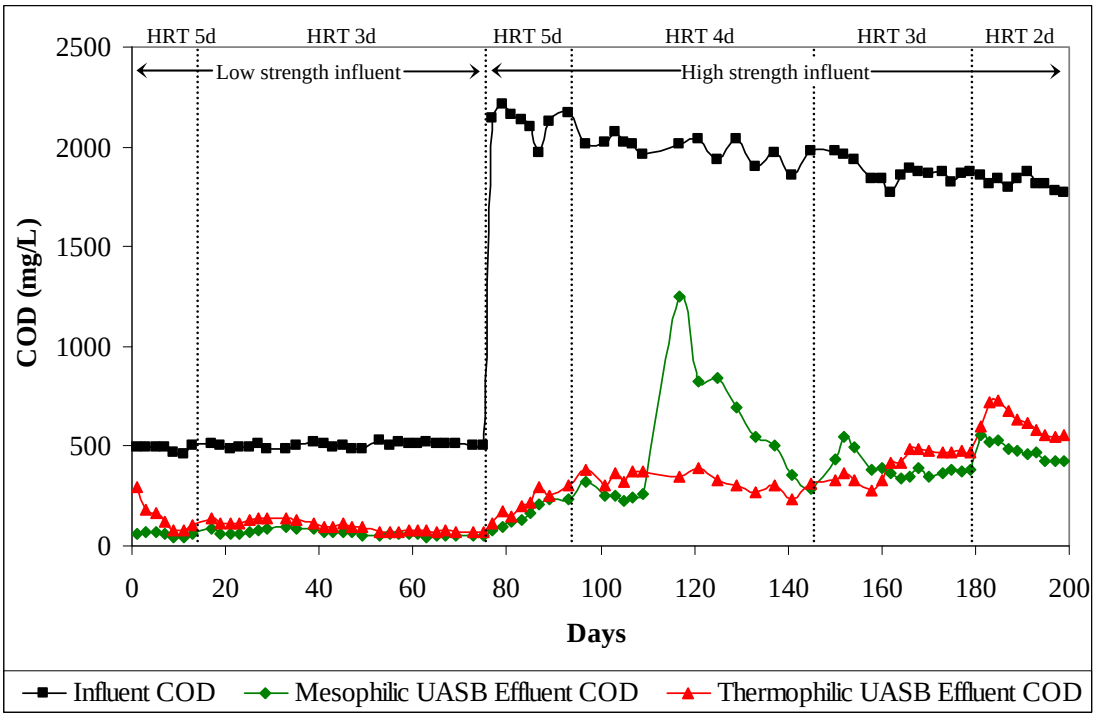


Figure 4.15 Influent and effluent COD concentrations in UASB reactors

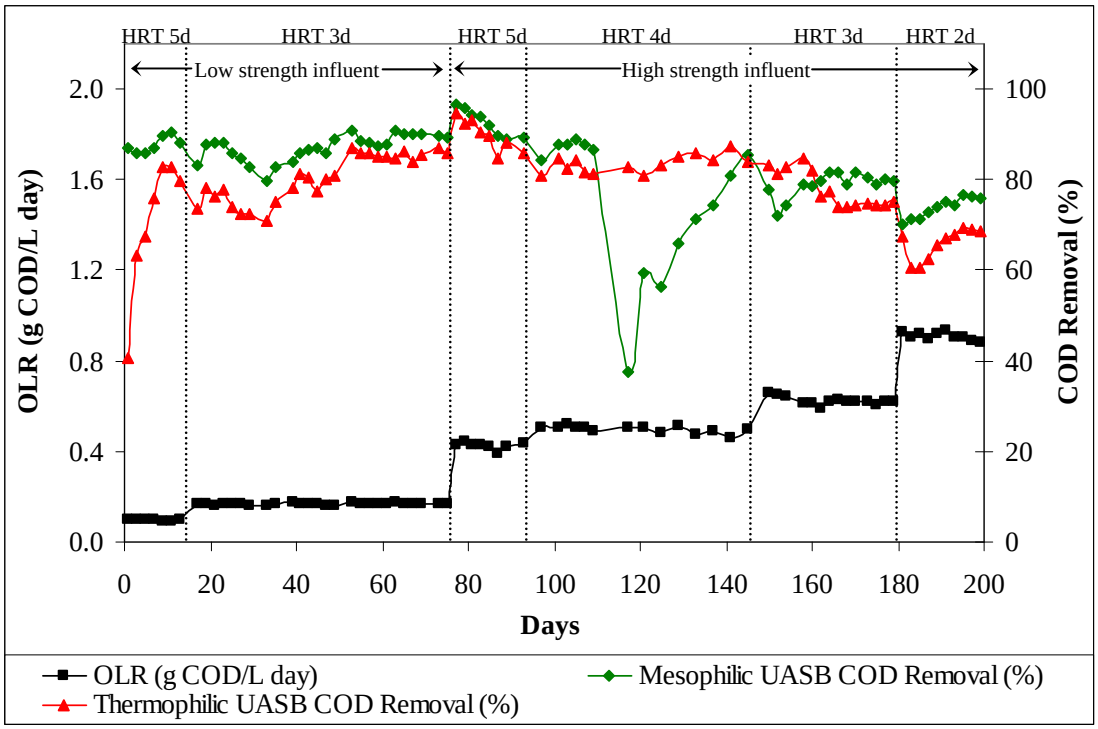


Figure 4.16 OLR and COD removal in UASB reactors

The mesophilic reactor reached steady state in the first week with effluent COD of 43-71 mg/L while the steady state of thermophilic reactor was reached after nine days with effluent COD of 78-101 mg/L. The COD removal efficiencies ranged from 86 to 91% and 80 to 83% for mesophilic and thermophilic UASB reactors, respectively. The average COD removal efficiencies and average effluent COD concentration at steady state condition in mesophilic UASB reactor were 88% and 60 mg/L, respectively and in thermophilic UASB reactor were 82% and 95 mg/L, respectively. Statistical analysis (ANOVA; $P<0.05$) showed that COD removal was significantly higher at the mesophilic UASB reactor than at the thermophilic UASB reactor.

After 13 days, the HRT was decreased from five to three days. The UASB reactors were operated with average influent COD concentration of 505 mg/L. The organic loading rate (OLR) increased from 0.10 to 0.17 g COD/L·day at which the COD removals ranged from 80 to 91% and 71 to 87% for mesophilic and thermophilic UASB reactors, respectively. The removal efficiency of the mesophilic UASB

dropped slightly when the HRT of the reactor was reduced; however, that of the thermophilic UASB reactor decreased sharply and thereafter the efficiencies started to increase slowly in the following three weeks. The mesophilic UASB reactor reached steady state with average COD removal of 87% while the average COD removal of the thermophilic UASB reactor was 80%. The average effluent COD concentration at steady state was 65 mg/L and 83 mg/L for mesophilic and thermophilic UASB reactors, respectively. The mesophilic UASB reactor had higher COD removal than the thermophilic UASB reactor. A similar observation was also made by Chung (1997) in the treatment of a synthetic wastewater. The COD removals were found to be 83% and 76% in mesophilic and thermophilic UASB reactors, respectively (Chung, 1997). In present study, the mesophilic and thermophilic UASB reactors showed no significant change in COD removal (ANOVA; $P<0.05$) as the HRT was decreased from five to three days with low strength pharmaceutical wastewater. Furthermore, at HRT of four days, COD removal was significantly greater at the mesophilic temperature than at the thermophilic temperature (ANOVA; $P<0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From day 76, the UASB reactors were fed with high strength wastewater (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. The OLR increased from 0.39 to 0.94 g COD/L·day with the feed of high strength wastewater. The HRT was initially increased from three to five days to avoid shock loading in the reactors. From day 76 to day 93, the UASB reactors were operated at HRT of five days with influent COD concentration of 1970-2217 mg/L. Though the HRT was increased but the average OLR was still increased from 0.17 to 0.43 g COD/L·day due to the higher influent COD concentration of the wastewater collected from the factory. The COD removal efficiencies varied from 89 to 96% and 85 to 95% for mesophilic and thermophilic UASB reactors, respectively, while the effluent COD concentrations ranged from 76 to 234 mg/L and 115 to 305 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD removal efficiency of both UASB reactors increased rapidly, although the effluent COD concentration increased sharply in the two days. After four days, the COD removals were decreased slightly. The average COD removal efficiencies at steady state conditions were 93% and 90%

for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentration in mesophilic UASB reactor was 158 mg/L while that in thermophilic UASB reactor was 213 mg/L. The results indicated that the thermophilic UASB reactor was more stable worked with high strength wastewater, unlike the mesophilic reactor that was steady in both characteristics of wastewater. Furthermore, higher COD removal efficiencies were achieved by both reactors when treating a higher concentration wastewater at HRT of five days. The mesophilic and thermophilic UASB reactors showed a significantly higher COD removal (ANOVA; $P<0.05$) as the HRT was increased from three to five days and as OLR increased due to the increase of COD concentration. However, the COD removal in mesophilic temperature at HRT of five days was not significantly difference from that at thermophilic temperature (ANOVA; $P<0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From 94 day to day 145, the UASB reactors were operated at HRT of four days. The OLR increased from 0.43 to 0.50 g COD/L·day and the influent COD ranged from 1853 to 2073 mg/L. The COD removal decreased rapidly in both UASB reactors in four days because of COD shock loading, although, in the next four days the COD removal increased faintly. The COD removal efficiencies ranged from 81 to 89% and 81 to 87% for mesophilic and thermophilic UASB reactors, respectively. The effluent COD concentrations ranged from 225 to 353 mg/L and 237 to 386 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentrations and the percentage COD removals at steady state were 262 mg/L and 87% for mesophilic UASB reactor and 329 mg/L and 83% for thermophilic UASB reactor, respectively. Based on statistical analysis (ANOVA; $P<0.05$), the COD removal at HRT of four days was significantly decreased if it was compared with the COD removal at HRT of five days for both UASB reactors.

On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The temperature increased to 60°C in one day and some sludge was washed out. From day 111 to day 118, the mesophilic UASB reactor was operated at ambient temperature (24±2°C) while it was being repaired. The COD concentration

increased sharply from 260 to 1254 mg/L. The percentage removal in the reactor during the upset period was not included in data analysis. After 30 days, the reactor stabilized with COD effluent of 353 mg/L and the COD removal efficiency reached 81%.

Leitao et al. (2006) reviewed the effect of temperature shock on the anaerobic reactor performance. The anaerobic reactor operated under steady state conditions when it exposed to a sudden temperature change, the process could become unbalanced due to the different response of the various metabolic groups of microorganism. A temperature shock might cause an immediate pH drop in the anaerobic reactor. Then, it would stabilize at pH that was slightly lower than the previous steady state pH. This phenomenon was due to an increase of the VFA. The effluent COD increased due to the increase of effluent VFA and suspended solids concentrations (Leitao et al., 2006).

From day 146 to day 179, the UASB reactors were operated at HRT of three days with influent COD concentration of 1773-1977 mg/L. The COD removal efficiency of the mesophilic UASB dropped roughly in seven days from 85 to 72%, although it increased again in the next six days. It seems the reactor was still sensitive to organic loading due to its previous failure (temperature shock). In thermophilic UASB reactor, the COD removal efficiency decreased slightly in 16 days from 84 to 76%. The COD removal efficiencies varied from 72 to 82% and 74 to 85% for mesophilic and thermophilic UASB reactors, respectively, while the effluent COD concentrations ranged from 339 to 547 mg/L and 282 to 489 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average COD removal efficiencies at steady state conditions were 80% and 75% for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentration in mesophilic UASB reactor was 369 mg/L while in thermophilic UASB reactor was 464 mg/L. The mesophilic and thermophilic UASB reactors showed a significantly lower COD removal (ANOVA; $P<0.05$) as the OLR increased due to HRT decrease from four to three days. The OLR increased from 0.59 to 0.66 g COD/L·day. Furthermore, the COD removal at the mesophilic temperature at HRT of three days was

significantly higher from that at the thermophilic temperature (ANOVA; $P<0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

For the last 20 days, the UASB reactors were operated at HRT of two days. The average OLR was 0.91 g COD/L·day and the influent COD ranged from 1853 to 2073 mg/L. The COD removal decreased rapidly in both UASB reactors in two days because of COD shock loading, although, in the next two days the COD removal increased slightly in mesophilic UASB reactor from 70 to 71%, while in thermophilic UASB reactor the COD removal increased slightly in eight days from 60 to 65%. The COD removal efficiencies ranged from 70 to 76% and 60 to 69% for mesophilic and thermophilic UASB reactors, respectively. The effluent COD concentrations ranged from 424 to 553 mg/L and 549 to 726 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentrations and the percentage COD removals at steady state were 478 mg/L and 74% for mesophilic UASB reactor and 582 mg/L and 68% for thermophilic UASB reactor, respectively. Based on statistical analysis (ANOVA; $P<0.05$), COD removal at HRT of two days was significantly decreased compared to COD removal at HRT of three days in both UASB reactors. Moreover, the COD removal at the mesophilic temperature at HRT of two days was significantly higher from that at the thermophilic temperature (ANOVA; $P<0.05$).

The performances of the UASB reactors were also evaluated based on $BOD_5$. From day 1 to day 13, the reactor was fed with influent $BOD_5$ of 299-311 mg/L at HRT of five days. The influent and effluent $BOD_5$ concentrations during this study in UASB reactors are shown in Figure 4.17. The $BOD_5$ removal efficiencies ranged from 88 to 93% and 87 to 90% for mesophilic and thermophilic UASB reactors, respectively. The effluent $BOD_5$ concentrations were from 20 to 36 mg/L and 31 to 39 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average $BOD_5$ removal efficiency and average effluent $BOD_5$ concentration in mesophilic UASB reactor at steady state condition was 91% and 27 mg/L, respectively, while the average $BOD_5$ removal of 88% and average effluent $BOD_5$

concentration of 35 mg/L were achieved in thermophilic UASB reactor. The $BOD_5$ removal in UASB reactors during this study is shown in Figure 4.18.

The $BOD_5$/COD ratio of the pharmaceutical wastewater varied from 0.62 to 0.72. Even though the $BOD_5$ and COD concentrations of the wastewater were fluctuated a lot but the $BOD_5$/COD ratio was relatively constant. The average $BOD_5$ removal and $BOD_5$/COD ratio during this study in UASB reactors are shown in Figure 4.19. At HRT of five days, the $BOD_5$/COD ratio of the pharmaceutical wastewater that was fed to the UASB reactors was 0.62. After being treated by the UASB reactors, the $BOD_5$/COD ratios were 0.45 and 0.37 for mesophilic and thermophilic temperatures, respectively. The $BOD_5$/COD ratio in thermophilic UASB reactor was lower than in mesophilic UASB reactor. On the other hand, the performance of thermophilic UASB reactor was worse than the mesophilic reactor. From the observation, the degradation of organic matter in thermophilic UASB reactor was more dominantly influence by the degradation of biodegradable organic matter $BOD_5$ than COD.

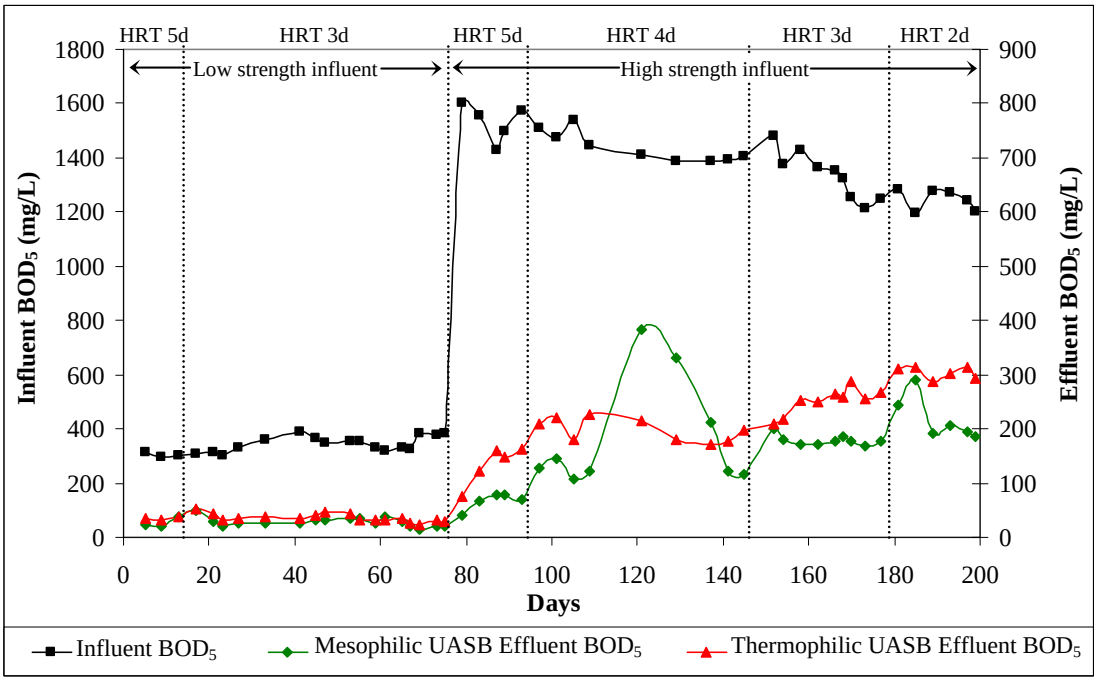


Figure 4.17 Influent and effluent $BOD_5$ concentrations in UASB reactors

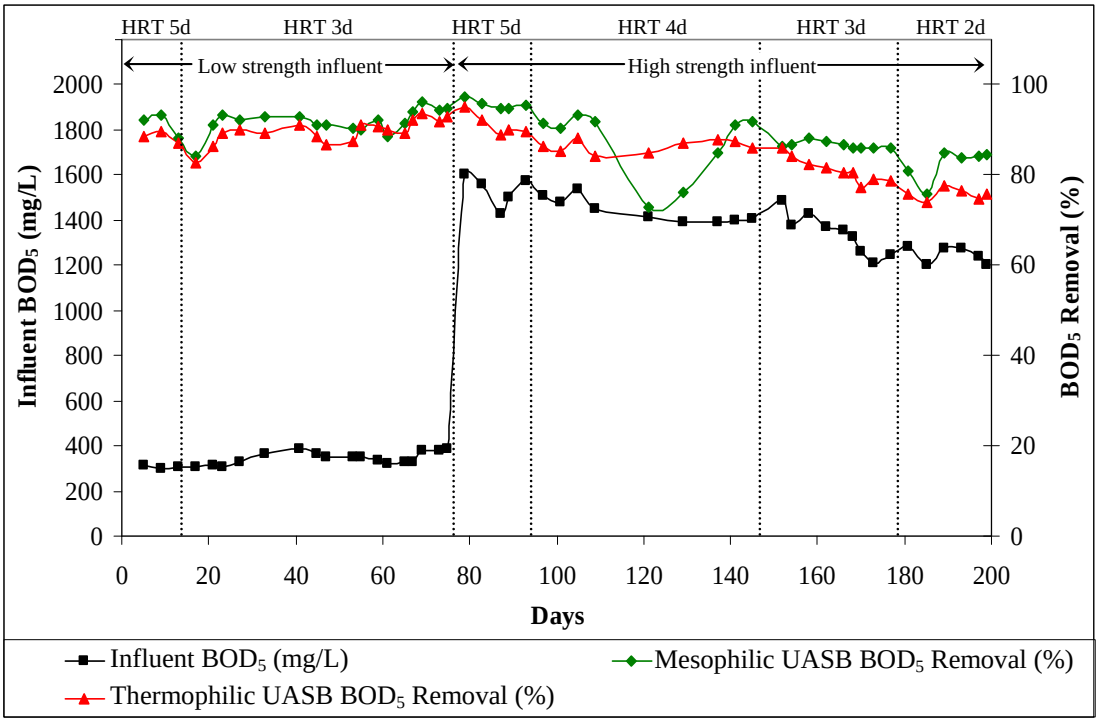


Figure 4.18 Influent $BOD_5$ concentration and $BOD_5$ removal in UASB reactors

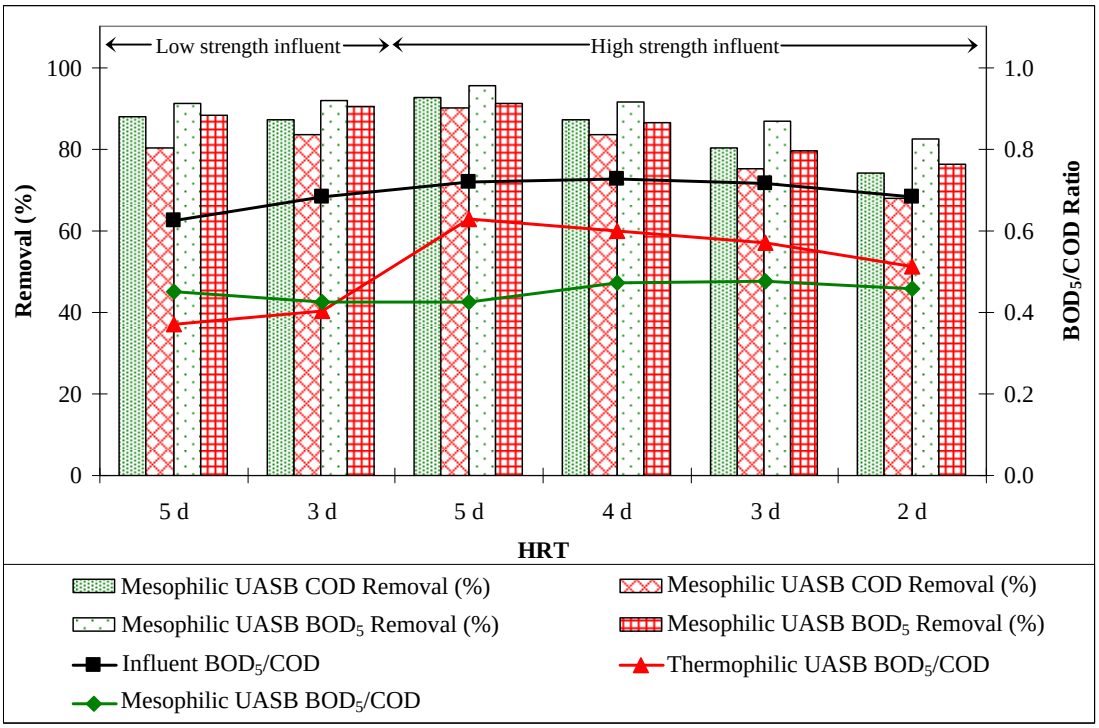


Figure 4.19 Average $BOD_5$ and COD removals and $BOD_5$/COD ratio in UASB reactors at steady state condition

After 13 days, the HRT was decreased from five to three days. The $BOD_5$ concentration ranged from 305 to 386 mg/L. The effluent concentrations were from 14 to 49 mg/L and 24 to 53 mg/L for mesophilic and thermophilic UASB reactors, respectively, while the $BOD_5$ removal efficiencies ranged from 84 to 96% and 83 to 94% for mesophilic and thermophilic UASB reactors, respectively. At steady state condition, the average effluent $BOD_5$ concentration and average $BOD_5$ removal were 28 mg/L and 92% respectively, in mesophilic UASB reactor and 34 mg/L and 90% respectively, in thermophilic UASB reactor. The influent $BOD_5$/COD ratio was 0.68 while the $BOD_5$/COD ratios of the mesophilic and thermophilic UASB reactors were 0.43 and 0.40, respectively.

From day 76, the UASB reactors were fed with high strength wastewater with $BOD_5$ concentration of 1198-1600 mg/L at HRTs of five, four, three and two days. The $BOD_5$/COD ratio of high strength pharmaceutical wastewater ranged from 0.68 to 0.72. From day 76 to day 93, the UASB reactors were operated at HRT of five days with $BOD_5$ concentration of 1427-1600 mg/L. The $BOD_5$ removal efficiencies varied from 95 to 97% and 89 to 95% for mesophilic and thermophilic UASB reactors, respectively, while the effluent $BOD_5$ concentrations ranged from 42 to 79 mg/L and 77 to 163 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average $BOD_5$ removal efficiencies at steady state conditions were 96% and 91% for mesophilic and thermophilic UASB reactors, respectively. The average effluent $BOD_5$ concentration in mesophilic UASB reactor was 67 mg/L while it was 134 mg/L in thermophilic UASB reactor. The $BOD_5$/COD ratio of pharmaceutical wastewater was 0.72 while the $BOD_5$/COD ratios of the mesophilic and thermophilic UASB reactors were 0.43 and 0.63, respectively.

From day 94 to day 145, the UASB reactors were operated at HRT of four days. The influent $BOD_5$ ranged from 1388 to 1540 mg/L and effluent $BOD_5$ ranged from 107 to 144 mg/L and 171 to 228 mg/L for mesophilic and thermophilic UASB reactors, respectively. The $BOD_5$ removal efficiencies ranged from 90 to 93% and 84 to 88% for mesophilic and thermophilic UASB reactors, respectively. The average effluent $BOD_5$ concentrations and percentage $BOD_5$ removals at steady state were

124 mg/L and 92% for mesophilic UASB reactor and 197 mg/L and 86% for thermophilic UASB reactor, respectively. The $BOD_5$/COD ratio of influent was 0.72 while the $BOD_5$/COD ratios of the mesophilic and thermophilic UASB reactors were 0.47 and 0.60, respectively. During the mesophilic UASB reactor breakdown period, the $BOD_5$ removal efficiency dropped from 92 to 73% while the $BOD_5$ concentration was 382 mg/L. After about a month, the mesophilic UASB stabilized at the $BOD_5$ removal of 92% and $BOD_5$ effluent concentration of 117 mg/L. Reactor performance during breakdown was not included in data analysis.

From day 146 to day 179, the UASB reactors were operated at HRT of three days with influent $BOD_5$ of 1212-1483 mg/L, while for the last 20 days, the UASB reactors were operated at HRT of two days with influent $BOD_5$ of 1198-1280 mg/L. The $BOD_5$ removal efficiencies in mesophilic UASB reactor varied from 86 to 88% and 76 to 85% for HRTs of three and two days, respectively, while the effluent concentrations ranged from 169 to 201 mg/L and 185 to 290 mg/L for HRTs of three and two days, respectively.

The $BOD_5$/COD ratios in mesophilic UASB reactor decreased from 0.71 to 0.48 and 0.68 to 0.46 for HRTs of three and two days, respectively. The $BOD_5$ removal efficiencies in thermophilic UASB reactor ranged from 77 to 86% and 74 to 78% for HRTs of three and two days, respectively. The $BOD_5$ effluent concentrations ranged from 210 to 287 mg/L and 287 to 314 mg/L for HRTs of three and two days, respectively. The $BOD_5$/COD ratios in thermophilic UASB reactor were 0.57 and 0.51 for HRTs of three and two days, respectively.

The average $BOD_5$ removal efficiencies at steady state conditions were 87% and 80% for mesophilic and thermophilic UASB reactors at HRT of three days, respectively and at HRT of two days were 82% and 76% for mesophilic and thermophilic UASB reactors, respectively. The average effluent $BOD_5$ concentration of 175 mg/L was reached in mesophilic UASB reactor at steady state while the average effluent $BOD_5$ concentration of 264 mg/L was achieved in thermophilic UASB reactor at HRT of three days. At HRT of two days, the average effluent $BOD_5$ concentrations of

219 mg/L and 299 mg/L were reached in mesophilic and thermophilic UASB reactors respectively at steady state condition.

### 4.2.2 COD and $BOD_5$ in Mesophilic and Thermophilic HUASB Reactors

The HUASB reactors were put in operation 62 days after the UASB reactors. For the first 12 days, the HUASB reactors were fed with low strength wastewater at HRT of three days. The reactors were fed with influent COD concentration of 503-519 mg/L with OLR of 0.16-0.18 g COD/L·day. The COD concentration in HUASB reactors is shown in Figure 4.20 and the HUASB reactors performance in this study is shown in Figure 4.21. The COD removal efficiency ranged from 84 to 92% and 46 to 69% for mesophilic and thermophilic HUASB reactors, respectively. The average COD removal efficiencies at steady state conditions were 88% and 66% for mesophilic and thermophilic HUASB reactors, respectively. Statistical analysis (ANOVA; $P<0.05$) showed that there was significant difference in the COD removal of the mesophilic and thermophilic HUASB reactors at HRT of three days.

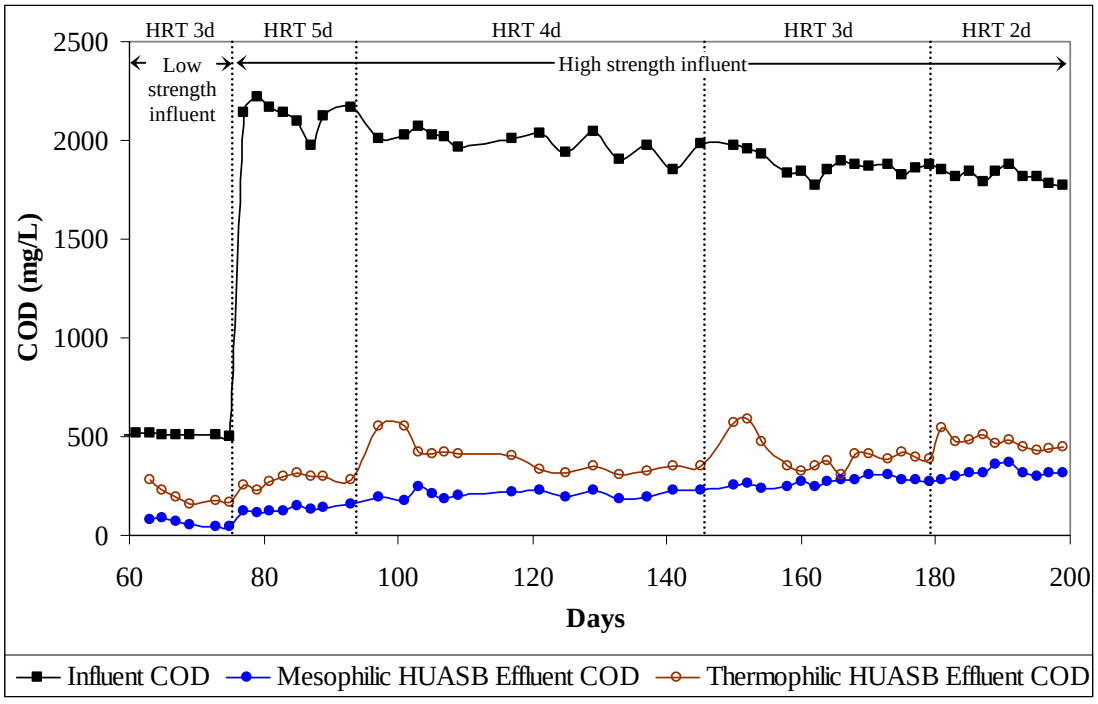


Figure 4.20 Influent and effluent COD concentrations in HUASB reactors

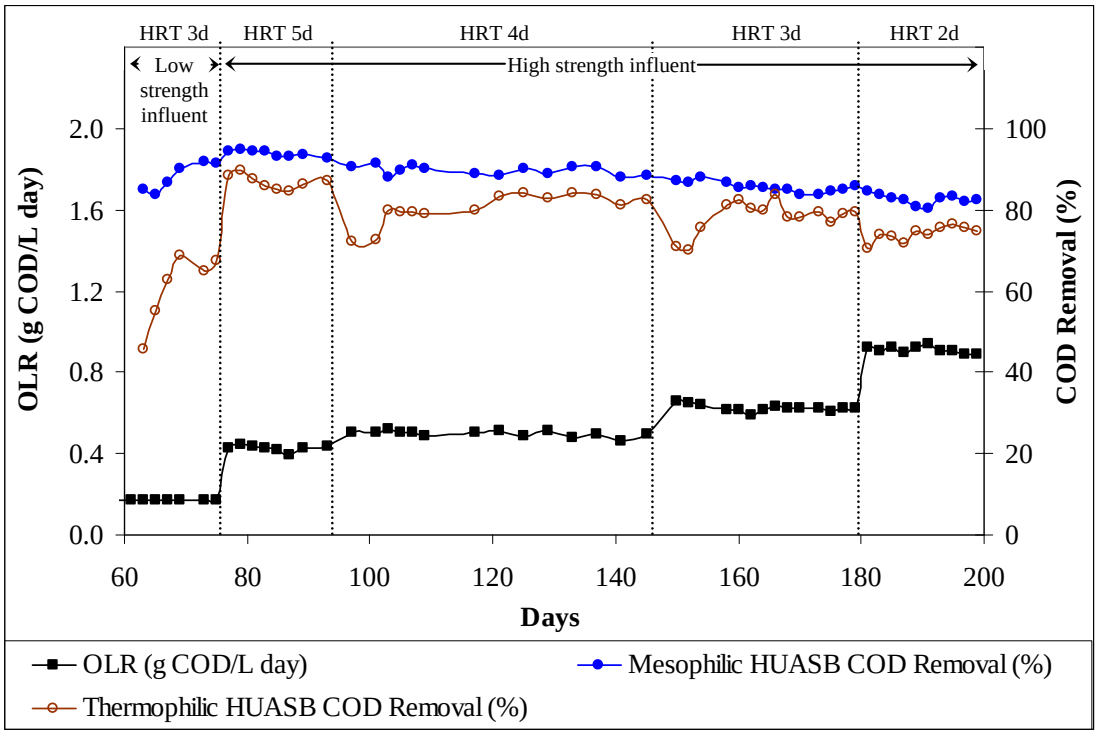


Figure 4.21 OLR and COD removal in HUASB reactors

After 12 days, the reactors were fed with high strength wastewater at HRTs of five, four, three and two days. The HUASB reactors were fed with influent COD concentration of 1170-2217 mg/L with OLR ranged from 0.39 to 0.94 g COD/L·day. From day 76 to day 93, the HUASB reactors were operated at HRT of five days and the average OLR was 0.43 g COD/L·day at which the COD removals ranged from 93 to 95% and 85 to 90% for mesophilic and thermophilic HUASB reactors, respectively. The HUASB reactors were operated with influent COD concentration of 1970-2217 mg/L. The removal efficiency of the mesophilic HUASB increased slightly when the HRT of reactor was changed to two days. However, the efficiency of the thermophilic HUASB reactor increased sharply from 68 to 88% in two days. Furthermore, the effluent COD concentrations increased sharply in both HUASB reactors due to the increase in influent concentration. The mesophilic HUASB reactor reached steady state with average COD removal of 94% while the average COD removal of the thermophilic HUASB reactor was 87%. The average effluent COD concentrations were 133 mg/L and 281 mg/L for mesophilic and thermophilic HUASB reactors, respectively. In addition, the mesophilic and thermophilic HUASB

reactors showed a significantly increase in COD removal (ANOVA; $P<0.05$) as the HRT was increased from three to five days with the feed of high strength pharmaceutical wastewater. Furthermore, at each HRT, the COD removal was significantly greater in the mesophilic temperature than in the thermophilic temperature (ANOVA; $P<0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From day 94 to day 145, the HUASB reactors were operated at HRT of four days and the average influent COD concentration of 1989 mg/L. The OLR ranged from 0.46 to 0.52 g COD/L·day. The COD removal efficiency of the mesophilic HUASB dropped slightly to reach steady state conditions within three day, whereas the COD removal dropped sharply from 85 to 72% in thermophilic HUASB reactor. The effluent COD concentrations ranged from 177 to 247 mg/L and 304 to 556 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The HUASB reactor reached steady state after nine days and the average COD removal was 82% while in mesophilic HUASB reactor, the average COD removal was 90%. The average effluent COD concentration in mesophilic HUASB reactor was 208 mg/L while in thermophilic UASB reactor was 366 mg/L. The mesophilic HUASB reactor showed a significantly lower COD removal (ANOVA; $P<0.05$) as the HRT was decreased from five to four days. However, the thermophilic HUASB reactor showed no significant difference in COD removal (ANOVA; $P<0.05$). Furthermore, the COD removal at mesophilic temperature was significantly higher from that at thermophilic temperature (ANOVA; $P<0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From day 146 to day 179, the HUASB reactors were operated at HRT of three days with influent COD concentration of 1773-1977 mg/L. The average OLR increased from 0.50 to 0.62 g COD/L·day. The COD removal decreased rapidly in thermophilic HUASB reactors in four days while in mesophilic HUASB reactor, the COD removal decreased faintly. The COD removal increased slightly after eight days. The result showed that the thermophilic HUASB reactor was more unstable worked with the changing of OLR, unlike the mesophilic reactor that was stable. The effluent COD

ranged from 234 to 304 mg/L and 305 to 591 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The COD removal efficiencies ranged from 84 to 88% and 70 to 84% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent COD concentration and percentage COD removal at steady state were 270 mg/L and 86% for mesophilic HUASB reactor and 382 mg/L and 79% for thermophilic HUASB reactor, respectively. Based on statistical analysis (ANOVA; $P<0.05$), the COD removal at HRT of three days was significantly decreased if it was compared with COD removal at HRT of four days in mesophilic HUASB reactor. While in thermophilic HUASB reactor, there was no significant difference between the COD removal at HRT of four days with HRT of three days.

From day 180 to day 199, the HUASB reactors were operated at HRT of two days with influent COD concentration of 1770-1877 mg/L. The OLR ranged from 0.89 to 0.94 g COD/L·day. The COD removal efficiency of the thermophilic HUASB dropped roughly in a day from 79 to 71%, after which it increased slightly. It might be due to the organic shock loading that resulted from the increased wastewater flow rate. The average OLR increased from 0.62 to 0.91 g COD/L·day. In mesophilic HUASB reactor; however, the COD removal efficiency decreased only marginally from 86 to 85%. The COD removal efficiencies varied from 80 to 85% and 71 to 76% for mesophilic and thermophilic HUASB reactors, respectively, while the effluent COD concentrations ranged from 285 to 371 mg/L and 432 to 545 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average COD removal efficiencies at steady state conditions were 83% and 74% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent COD concentration in mesophilic UASB reactor was 319 mg/L while in thermophilic HUASB reactor was 473 mg/L. The mesophilic HUASB reactor showed no significant difference in the COD removal (ANOVA; $P<0.05$) as the HRT was decreased from three to two days while the thermophilic HUASB reactor showed a significantly lower COD removal. Furthermore, the COD removal at mesophilic temperature at HRT of two days was significantly higher from that at thermophilic temperature (ANOVA; $P<0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

Nandy and Kaul (2001) observed that the decrease in conversion efficiency with reduction in HRT is greater at higher substrate concentration. It indicated that the system became more organically stressed at higher organic loading. Variation in HRT at constant organic substrate loading by varying feed substrate concentration indicates that performance efficiency varies linearly; increasing with increase in HRT. By optimizing the substrate loading rate, the system can be operated at the loading either by increasing influent substrate concentration with high HRT or operating with low HRT and low influent substrate concentration. Nandy and Kaul (2001) showed that HRT between 5.0 and 2.5 days could be identified as critical, depending on feed substrate concentration.

The performances of the HUASB reactors were also evaluated in terms of $BOD_5$ removal from day 62 after the UASB reactors were operated. For the first 12 days, the reactors were fed with influent $BOD_5$ of 325-383 mg/L at HRT of three days. The $BOD_5$ concentration during this study in HUASB reactors is shown in Figure 4.22 and the $BOD_5$ removal in HUASB reactors during this study is shown in Figure 4.23. The $BOD_5$ removal efficiency in mesophilic HUASB reactor ranged from 90 to 95% while the $BOD_5$ removal in thermophilic HUASB reactor ranged from 70 to 80%. The effluent $BOD_5$ concentrations were from 20 to 36 mg/L and 31 to 39 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average $BOD_5$ removal efficiency and average effluent $BOD_5$ concentration in mesophilic HUASB reactor at steady state conditions were 93% and 27 mg/L, respectively, while the average COD removal of 83% and average effluent COD concentration of 83 mg/L were achieved in thermophilic HUASB reactor. The $BOD_5$/COD ratio in the wastewater ranged from 0.68 to 0.72 during the operation of the HUASB reactors. The average $BOD_5$ removal and $BOD_5$/COD ratio in HUASB reactors are shown in Figure 4.24. At HRT of three days, the $BOD_5$/COD ratio of low strength pharmaceutical wastewater was 0.68. After treatment by the HUASB reactors, $BOD_5$/COD ratios were 0.45 and 0.37 for mesophilic and thermophilic temperatures, respectively.

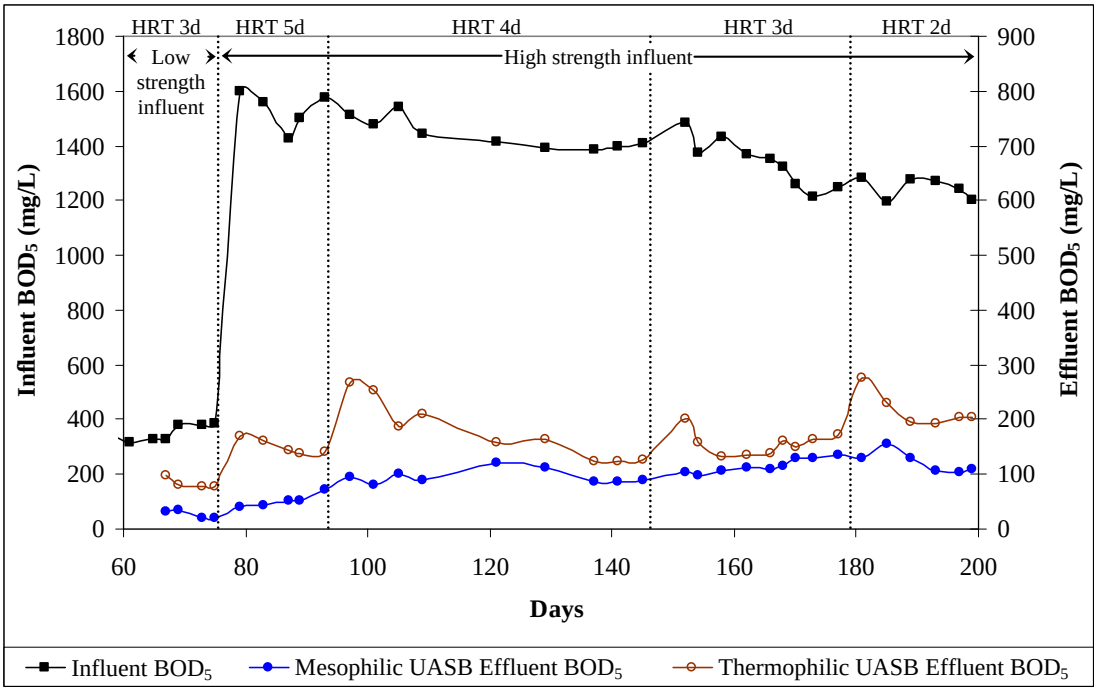


Figure 4.22 Influent and effluent $BOD_5$ concentrations in HUASB reactors

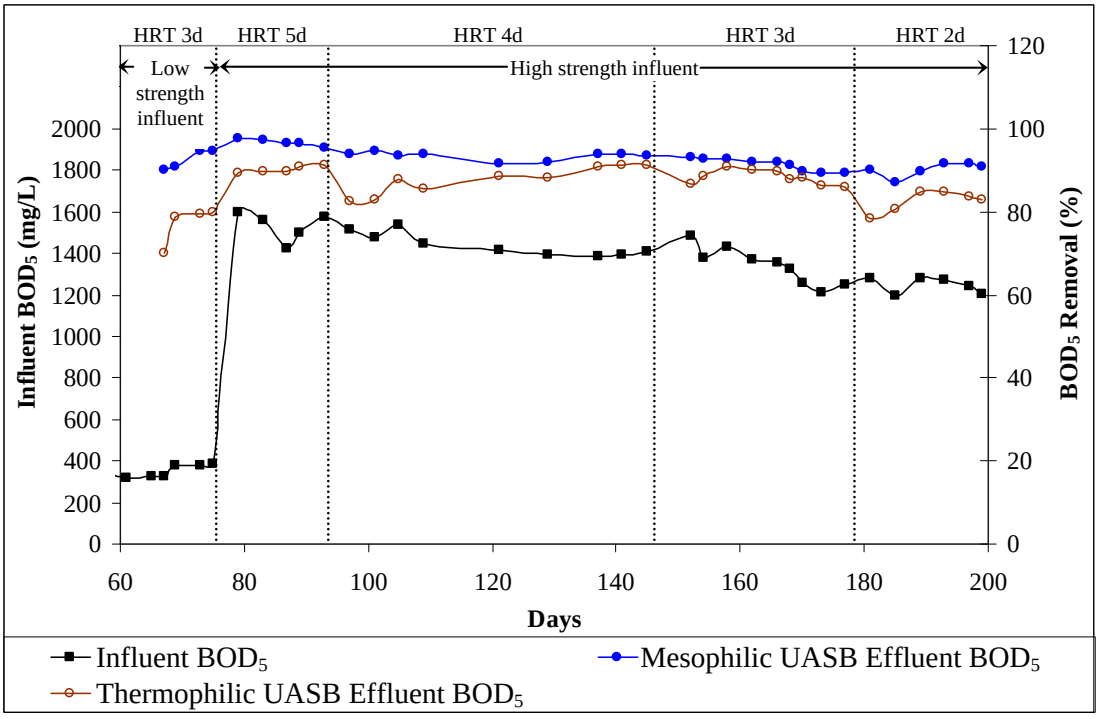


Figure 4.23 Influent $BOD_5$ concentration and $BOD_5$ removal in HUASB reactors

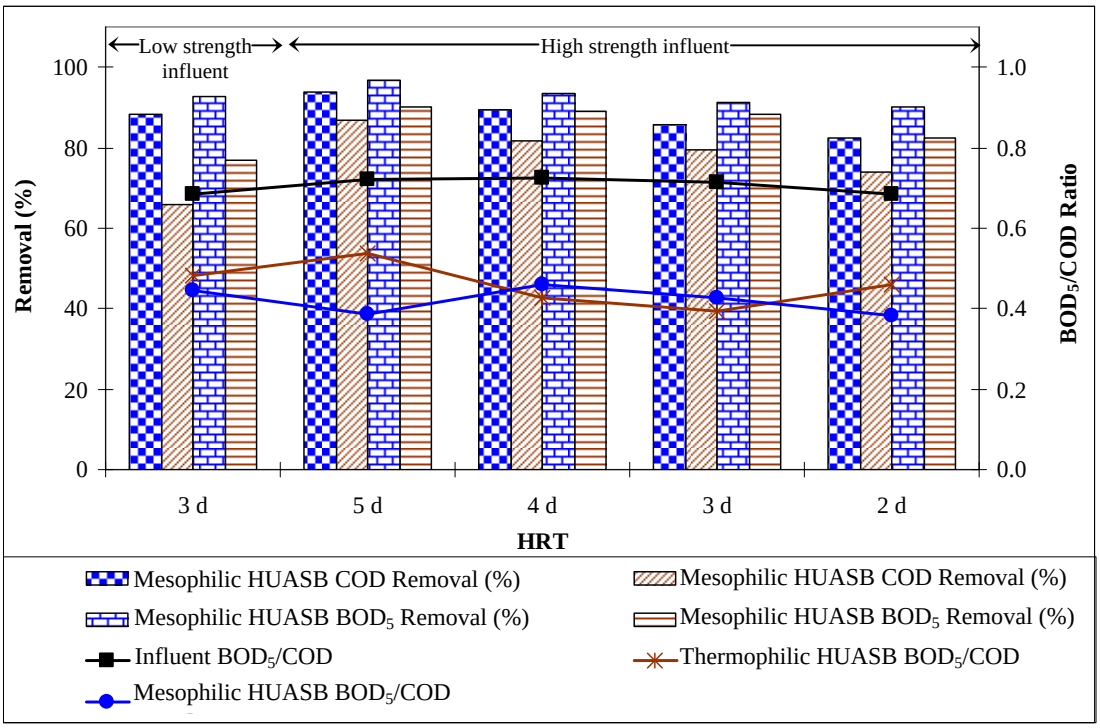


Figure 4.24 Average $BOD_5$ and COD removals and $BOD_5$/COD ratio in HUASB reactors at steady state condition

After 13 days, the HRT was increased from three to five days to avoid shock organic loading due to the increased pharmaceutical wastewater COD and $BOD_5$ concentrations. The average effluent $BOD_5$ concentration increased from 501 to 1938 mg/L. The $BOD_5$ concentration ranged from 1427 to 1600 mg/L. The effluent $BOD_5$ concentrations were from 40 to 71 mg/L and 138 to 171 mg/L for mesophilic and thermophilic HUASB reactors, respectively, while the $BOD_5$ removal efficiencies ranged from 95 to 97% and 89 to 91% for mesophilic and thermophilic HUASB reactors, respectively. At steady state conditions, the average effluent $BOD_5$ concentration and average $BOD_5$ removal were 51 mg/L and 97% in mesophilic HUASB reactor, respectively, whereas in thermophilic HUASB reactor were 151 mg/L and 90%, respectively. The $BOD_5$/COD ratio of pharmaceutical wastewater at HRT of five days was 0.72 while the $BOD_5$/COD ratio of the mesophilic and thermophilic HUASB reactors were 0.39 and 0.54, respectively.

From day 94 to day 145, the HUASB reactors were operated at HRT of four days with influent $BOD_5$ concentration of 1388-1540 mg/L. The $BOD_5$ removal efficiencies varied from 92 to 95% and 82 to 91% for mesophilic and thermophilic HUASB reactors, respectively, while the effluent $BOD_5$ concentrations ranged from 81 to 120 mg/L and 123 to 267 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average $BOD_5$ removal efficiencies at steady state conditions were 93% and 89% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent $BOD_5$ concentration in mesophilic HUASB reactor was 96 mg/L while in thermophilic HUASB reactor was 156 mg/L. The $BOD_5$/COD ratio of pharmaceutical wastewater at HRT of four days was 0.72 while the $BOD_5$/COD ratios of the mesophilic and thermophilic HUASB reactors were 0.46 and 0.43, respectively.

From day 146 to day 179, the HUASB reactors were operated at HRT of three days. The influent $BOD_5$ ranged from 1212 to 1483 mg/L and effluent $BOD_5$ ranged from 97 to 134 mg/L and 132 to 200 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The $BOD_5$ removal efficiencies ranged from 89 to 93% and 86 to 91% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent $BOD_5$ concentrations and $BOD_5$ removals at steady state were 115 mg/L and 91% for mesophilic HUASB reactor and 150 mg/L and 88% for thermophilic HUASB reactor, respectively. The $BOD_5$/COD ratio of influent was 0.71 while the $BOD_5$/COD ratios of the mesophilic and thermophilic HUASB reactors were 0.43 and 0.39, respectively.

For the last 20 days, the HUASB reactors were operated at HRT of two days with influent $BOD_5$ of 1198-1280 mg/L. The $BOD_5$ removal efficiencies in mesophilic and thermophilic HUASB reactors at HRT of two days varied from 87 to 92% and 83 to 84%, respectively, while the effluent $BOD_5$ concentrations ranged from 102 to 156 mg/L and 194 to 276 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The $BOD_5$/COD ratio in mesophilic HUASB reactor decreased from 0.68 to 0.38 while in thermophilic HUASB reactor decreased from 0.68 to 0.46. The average $BOD_5$ removal efficiencies at steady state conditions were 90% and 83%

for mesophilic and thermophilic HUASB reactors at HRT of two days, respectively. The average effluent $BOD_5$ concentration of 122 mg/L was reached in mesophilic HUASB reactor at steady state while the average effluent $BOD_5$ concentration of 218 mg/L was achieved in thermophilic HUASB reactor.

### 4.2.3 Summary of UASB and HUASB Reactors Performance

In Phase II study, the UASB and HUASB reactors were fed with low strength and high strength influent at HRTs of five, four, three and two days under mesophilic (35±2°C) and thermophilic (55±2°C) conditions. The performance of each reactor was evaluated in terms of COD and $BOD_5$ removals. Table 4.1 and Table 4.2 show the average COD and $BOD_5$ concentrations obtained from the UASB and HUASB reactors at steady state conditions. The objective of this study was to evaluate the performance of mesophilic and thermophilic UASB and HUASB reactors in treating non-penicillin pharmaceutical wastewater. The reactors were seeded with sludge from an aerobic domestic sewage treatment plant. The results show the HUASB reactors to be significantly more efficient in COD removal than the UASB reactors. The pharmaceutical wastewater was very fluctuative in COD and $BOD_5$ concentrations. The reactors were fed with low strength influent (COD 458-526 mg/L) and high strength influent (COD 1770-2217 mg/L). The reactors showed higher COD removal in treating high strength wastewater.

This study was also to evaluate the effect of HRT and temperature on the performance of UASB and HUASB reactors. The reactors were operated under mesophilic (35±2°C) and thermophilic (55±2°C) temperatures and HRTs of five, four, three and two days. The results show that the reactor performance was significantly affected by type of reactors, HRT and temperature. Both mesophilic UASB and HUASB reactors showed higher COD and $BOD_5$ removals in treating pharmaceutical wastewater.

Table 4.1 Average influent and effluent COD concentrations, OLR and COD removal in UASB and HUASB reactors

| HRT (days) | Influent COD (mg/L) | OLR (g COD/L·d) | Mesophilic UASB Eff. COD (mg/L) | Mesophilic UASB COD Rem. (%) | Thermophilic UASB Eff. COD (mg/L) | Thermophilic UASB COD Rem. (%) |
|---|---|---|---|---|---|---|
| Low strength influent | | | | | | |
| 5 | 487 | 0.10 | 60 | 88 | 95 | 80 |
| 3 | 505 | 0.17 | 65 | 87 | 83 | 84 |
| High strength influent | | | | | | |
| 5 | 2127 | 0.43 | 158 | 93 | 213 | 90 |
| 4 | 1989 | 0.50 | 262 | 87 | 329 | 83 |
| 3 | 1875 | 0.62 | 369 | 80 | 464 | 75 |
| 2 | 1820 | 0.91 | 478 | 74 | 582 | 68 |
| HRT (days) | Influent COD (mg/L) | OLR (g COD/L·d) | Mesophilic HUASB Eff. COD (mg/L) | Mesophilic HUASB COD Rem. (%) | Thermophilic HUASB Eff. COD (mg/L) | Thermophilic HUASB COD Rem. (%) |
| Low strength influent | | | | | | |
| 3 | 505 | 0.17 | 61 | 88 | 172 | 66 |
| High strength influent | | | | | | |
| 5 | 2127 | 0.43 | 133 | 94 | 281 | 87 |
| 4 | 1989 | 0.50 | 208 | 90 | 366 | 82 |
| 3 | 1875 | 0.62 | 270 | 86 | 382 | 79 |
| 2 | 1820 | 0.91 | 319 | 83 | 473 | 74 |

Table 4.2 Average influent and effluent $BOD_5$ concentrations and $BOD_5$ removal in UASB and HUASB reactors

| HRT (days) | Influent $BOD_5$ (mg/L) | Mesophilic UASB Eff. $BOD_5$ (mg/L) | Mesophilic UASB $BOD_5$ Rem. (%) | Thermophilic UASB Eff. $BOD_5$ (mg/L) | Thermophilic UASB $BOD_5$ Rem. (%) |
|---|---|---|---|---|---|
| Low strength influent | | | | | |
| 5 | 305 | 27 | 91 | 35 | 88 |
| 3 | 345 | 28 | 92 | 34 | 90 |
| High strength influent | | | | | |
| 5 | 1532 | 67 | 96 | 134 | 91 |
| 4 | 1441 | 124 | 92 | 197 | 86 |
| 3 | 1339 | 175 | 87 | 264 | 80 |
| 2 | 1245 | 219 | 82 | 299 | 76 |
| HRT (days) | Influent $BOD_5$ (mg/L) | Mesophilic HUASB Eff. $BOD_5$ (mg/L) | Mesophilic HUASB $BOD_5$ Rem. (%) | Thermophilic HUASB Eff. $BOD_5$ (mg/L) | Thermophilic HUASB $BOD_5$ Rem. (%) |
| Low strength influent | | | | | |
| 3 | 345 | 27 | 93 | 83 | 77 |
| High strength influent | | | | | |
| 5 | 1532 | 51 | 97 | 151 | 90 |
| 4 | 1441 | 96 | 93 | 156 | 89 |
| 3 | 1339 | 115 | 91 | 150 | 88 |
| 2 | 1245 | 122 | 90 | 218 | 83 |

The highest average COD and $BOD_5$ removals were achieved by the mesophilic HUASB reactor treating high strength pharmaceutical wastewater at HRT of five days (average OLR 0.43 g COD/L·day); average COD removal was 90%, average effluent COD was 133 mg/L, average $BOD_5$ removal was 97% and average effluent $BOD_5$ was 51 mg/L. The COD and $BOD_5$ removals decreased when the HRT was decreased. The lowest average COD and $BOD_5$ removals were achieved by the thermophilic UASB reactor at HRT of two days. The average COD and $BOD_5$ removals were 68% and 76%, respectively, whereas the average COD and $BOD_5$ concentrations were 582 mg/L and 299 mg/L, respectively.

From the two-way ANOVA result, it found that there was a significant effect of reactor configuration, HRT and temperature, so it implied that the mean of COD removal varied between HRTs of five, four, three and two days and temperature of mesophilic and thermophilic. In addition, there was statistical indication of interaction between HRT and type of reactor, thus the effect of HRT on the COD removal varied significantly with the variation of reactor. The COD removal differed due to the effect between HRT with temperature and reactor with temperature. The two-way ANOVA result showed the COD removal varied with the effect of three variable operation conditions. The detail of two-way ANOVA analysis is shown in APPENDIX B: Table B.2.

### 4.2.4 Nutrients in Mesophilic and Thermophilic UASB Reactors

Figure 4.25 to Figure 4.32 show the influent and effluent nutrient concentrations ($NH_3$-N, $NO_3$-N, TKN and TP) in UASB reactors. In the first 13 days, the UASB reactors were operated at HRT of five days and the influent $NH_3$-N and $NO_3$-N concentrations ranged from 3.0 to 3.7 mg/L and 0.6 to 0.9 mg/L, respectively. The effluent $NH_3$-N increased in both UASB reactors during this study, whereas the $NO_3$-N was not significantly difference between the influent and effluent of the UASB reactors. The effluent $NH_3$-N and $NO_3$-N concentrations in mesophilic UASB reactor ranged from 11.5 to 13.0 mg/L and 0.4 to 0.7 mg/L, respectively, while in thermophilic reactor they ranged from 18.5 to 13.0 mg/L and 0.1 to 0.4 mg/L, respectively.

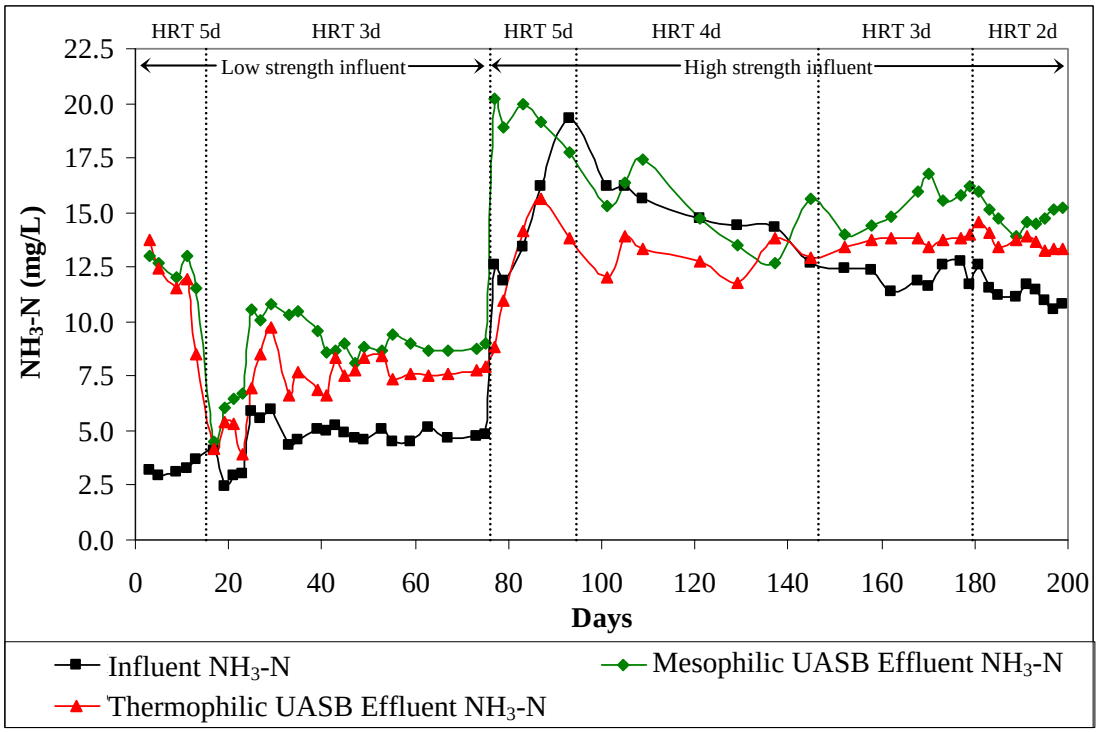


Figure 4.25 Influent and effluent $NH_3$-N concentrations in UASB reactors

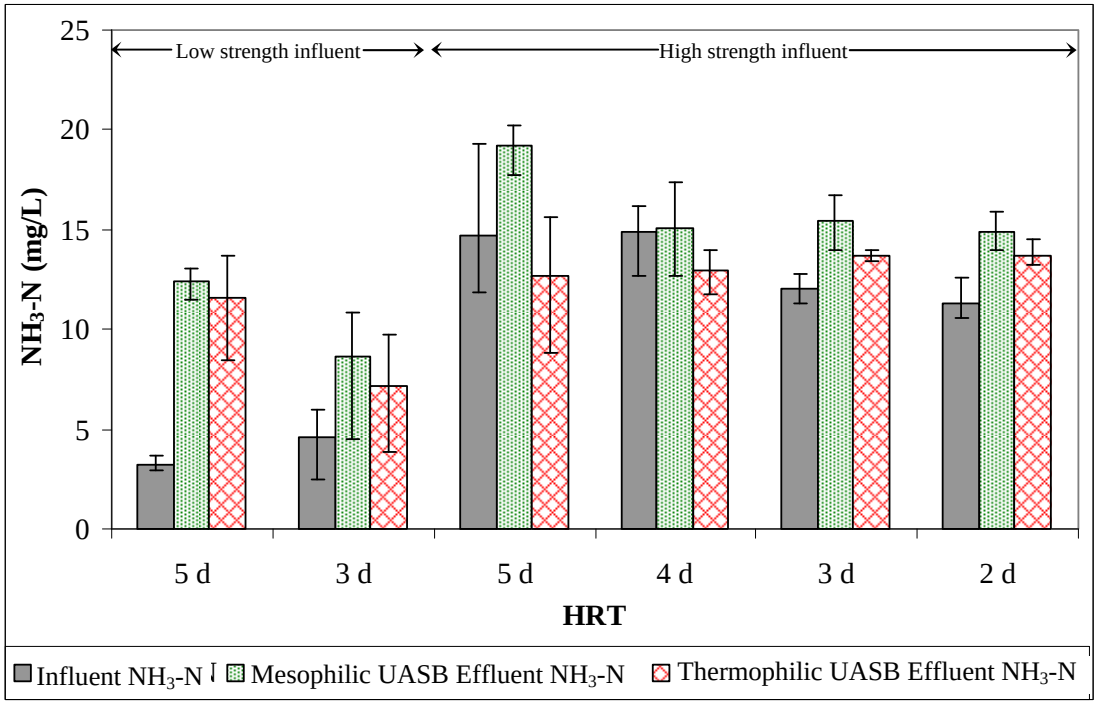


Figure 4.26 Average influent and effluent $NH_3$-N concentrations at each variation of HRT in UASB reactors

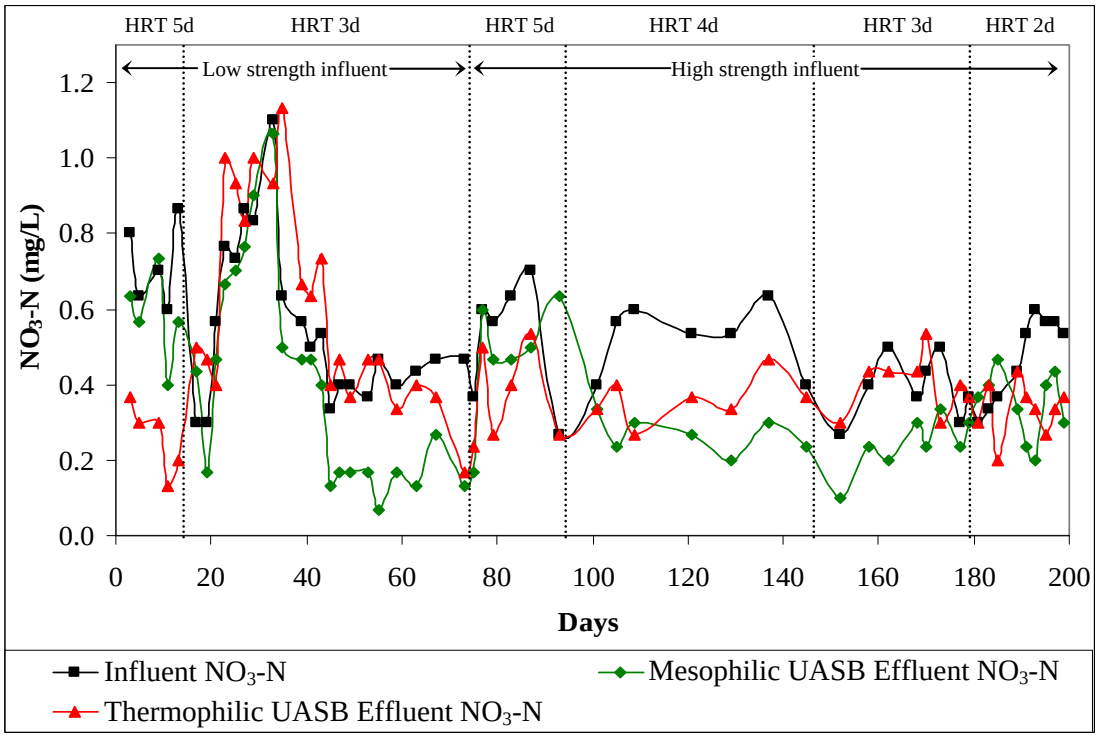


Figure 4.27 Influent and effluent $NO_3$-N concentrations in UASB reactors

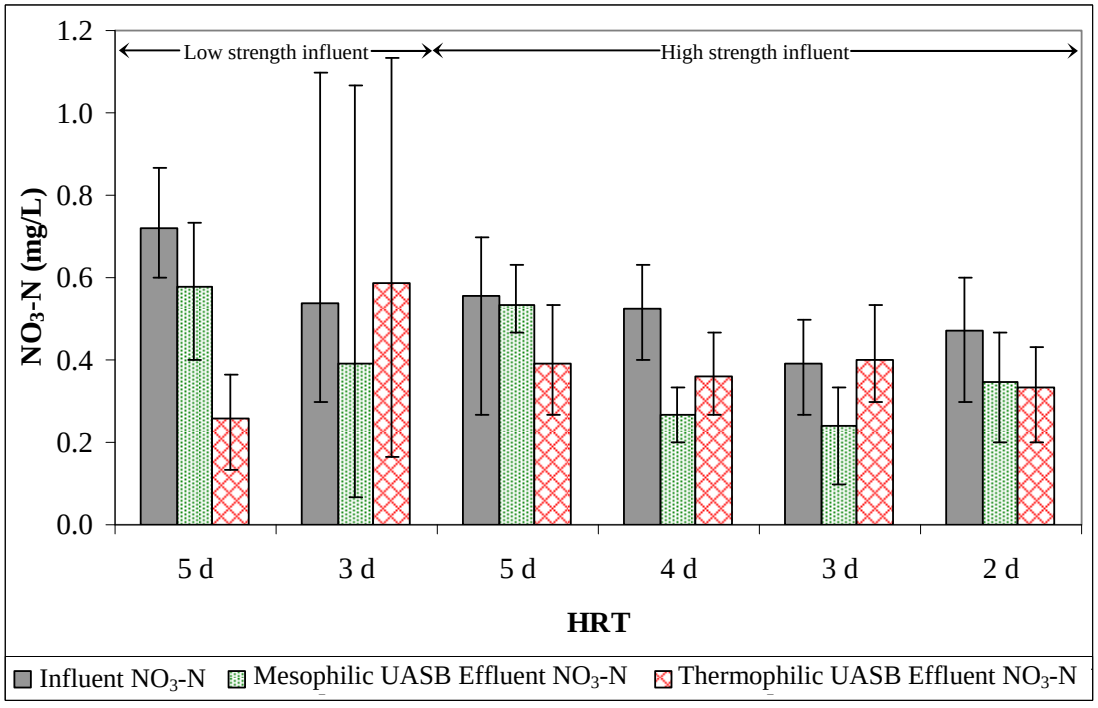


Figure 4.28 Average influent and effluent $NO_3$-N concentrations at each variation of HRT in UASB reactors

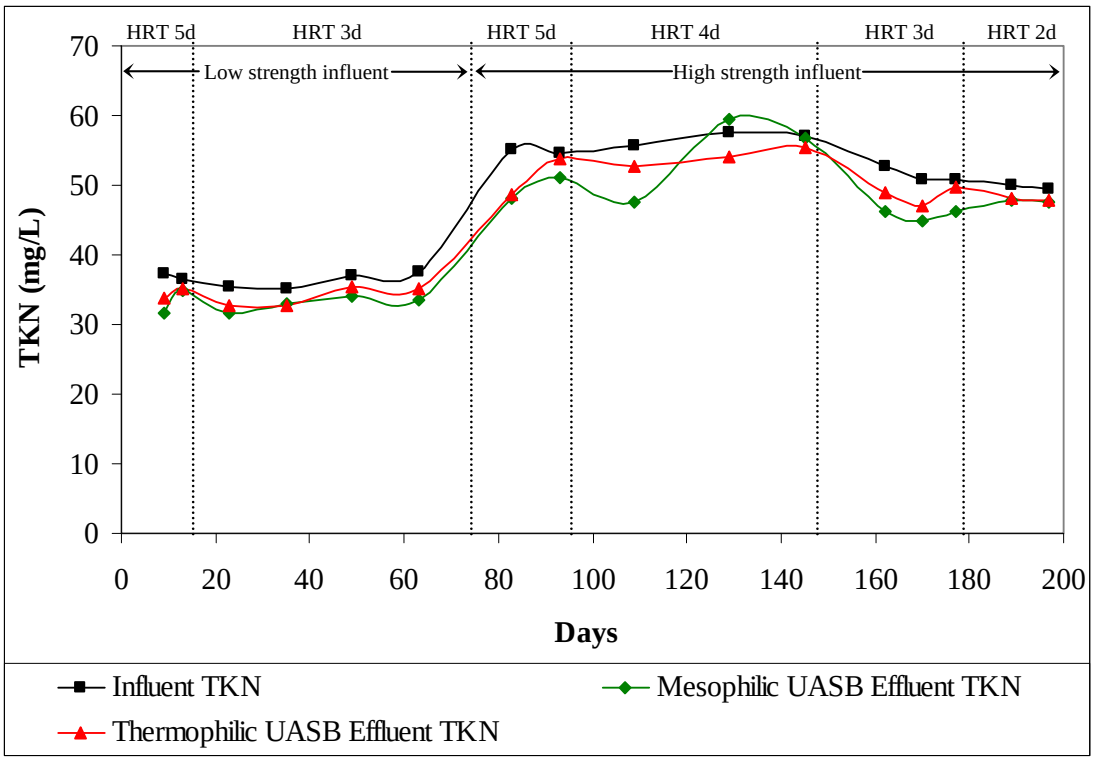


Figure 4.29 Influent and effluent TKN concentrations in UASB reactors

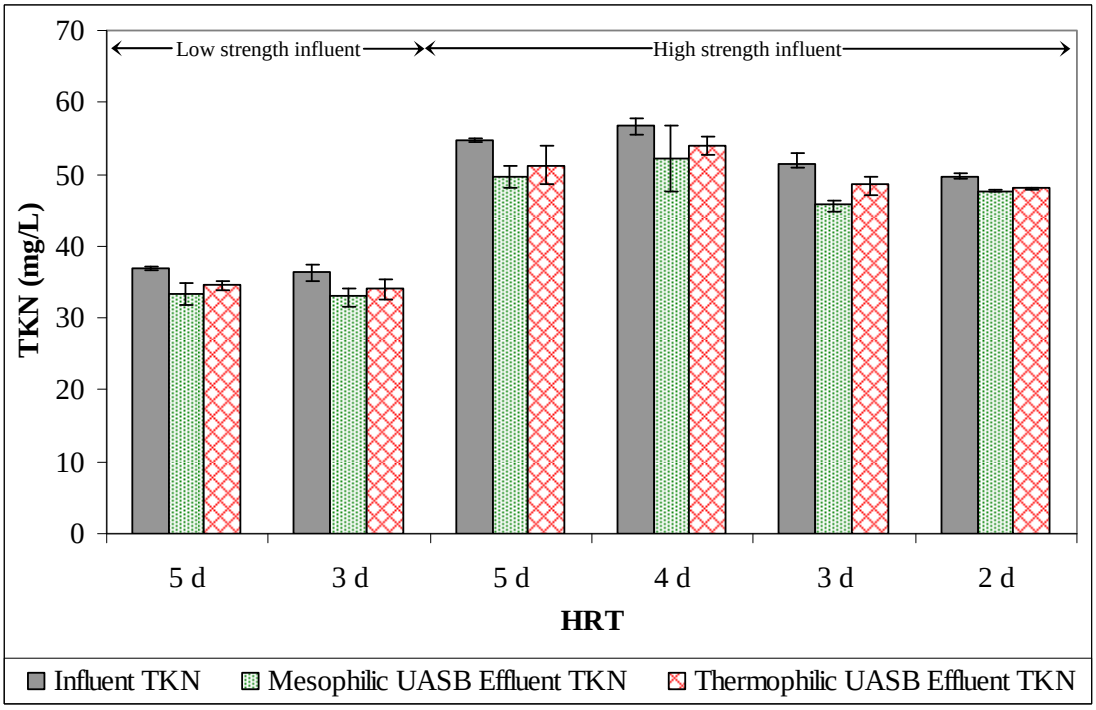


Figure 4.30 Average influent and effluent TKN concentrations at each variation of HRT in UASB reactors

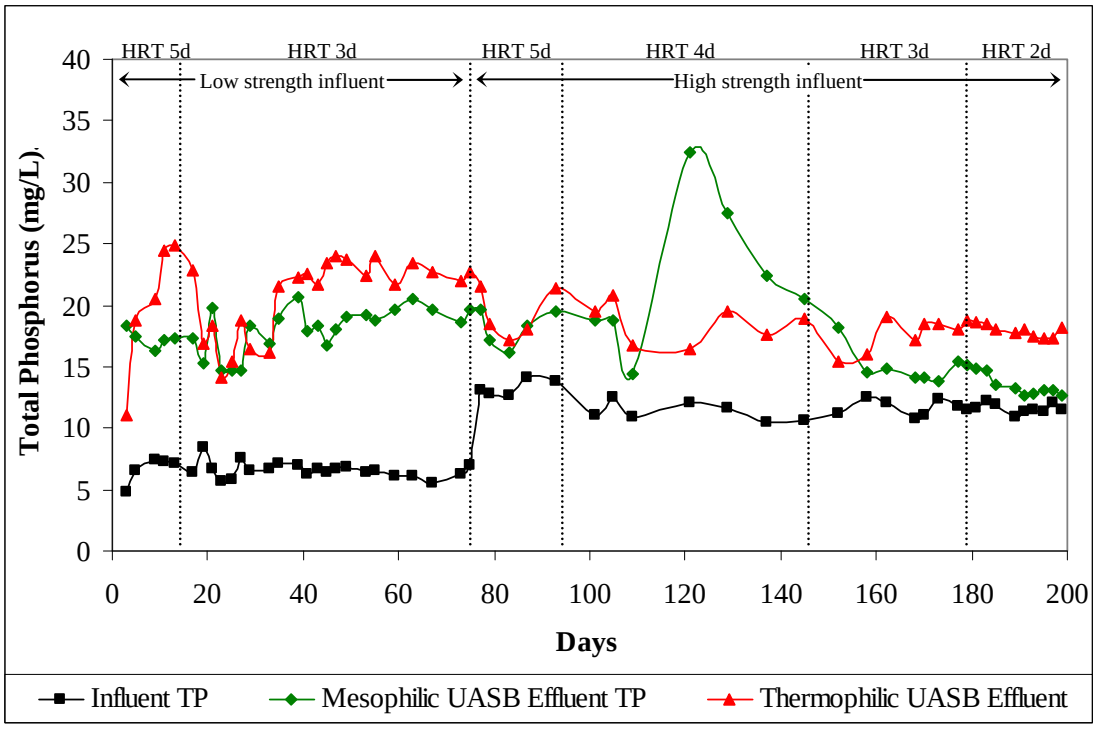


Figure 4.31 Influent and effluent TP concentrations in UASB reactors

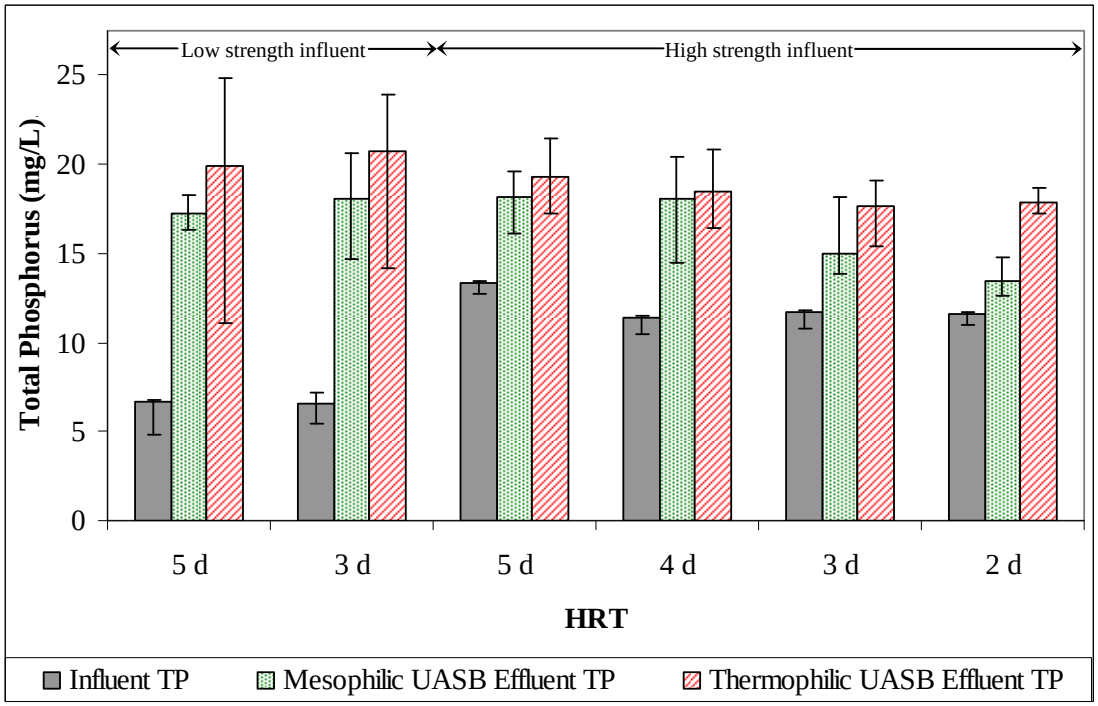


Figure 4.32 Average TP concentration at each variation of HRT in UASB reactors

In low strength pharmaceutical wastewater (COD 458-499 mg/L), the average TKN and TP concentrations of pharmaceutical wastewater were 36.9 mg/L and 6.6 mg/L, respectively at HRT of five days. The COD:TKN:TP ratio was 67:5:1. The average effluent TKN concentrations were 33.3 mg/L and 34.6 mg/L for mesophilic and thermophilic UASB reactors, respectively. Moreover, the average effluent TP concentrations were 17.3 mg/L and 19.9 mg/L. The average TKN and TP concentrations are shown in Figure 4.30 and Figure 4.32, respectively. The COD:TKN:TP ratios decreased from 67:5:1 to 3:2:1 and 4:2:1 for mesophilic and thermophilic UASB reactors, respectively.

At HRT of three days, the average effluent $NH_3$-N of the mesophilic UASB reactor was higher than the thermophilic UASB reactor whereas the average effluent $NO_3$-N of the mesophilic UASB reactor was lower than the thermophilic UASB reactor. The average $NH_3$-N concentrations increased from 4.6 to 8.7 mg/L and 4.6 to 7.2 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average $NO_3$-N concentrations were relatively constant from 0.4 to 0.5 mg/L and 0.5 to 0.6 mg/L for mesophilic and thermophilic UASB reactors, respectively. The influent and effluent $NH_3$-N and $NO_3$-N concentrations in UASB reactors during this study are shown in Figure 4.25 to Figure 4.28, respectively. From day 14 to day 75, the UASB reactors were fed by low strength pharmaceutical wastewater (COD 483-526 mg/L) and TP concentrations of pharmaceutical wastewater varied from 5.5 to 8.5 mg/L. The effluent TP concentrations in mesophilic and thermophilic UASB reactors ranged from 14.7 to 20.6 mg/L and 14.1 to 23.9 mg/L, respectively. The influent and effluent TP concentrations in UASB reactors during this study are shown in Figure 4.31. The average TKN concentration of pharmaceutical wastewater was 36.3 mg/L, while the average effluent TKN concentrations were 33.1 mg/L and 34 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD:TKN:TP ratios decreased from 79:6:1 to 3:2:1 and 5:2:1 for mesophilic and thermophilic UASB reactors, respectively.

From day 76, the UASB reactors were fed with high strength wastewater (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. At HRT of

five days, the average influent $NH_3$-N and $NO_3$-N concentrations were 14.7 mg/L and 0.6 mg/L, respectively. The $NH_3$-N concentration increased in mesophilic UASB reactor (from 14.7 to 19.2 mg/L) whereas in thermophilic UASB reactor, it decreased (from 14.7 to 12.7 mg/L). The $NO_3$-N concentrations slightly decreased in both UASB reactors. The average effluent $NO_3$-N concentrations in mesophilic and thermophilic UASB reactor were 0.5 mg/L and 0.4 mg/L, respectively. In high strength pharmaceutical wastewater (COD 1970-2217 mg/L) when the UASB reactors were operated at HRT of five days, the average TKN and TP concentrations of pharmaceutical wastewater were 54.8 mg/L and 13.3 mg/L, respectively. The COD:TKN:TP ratio of pharmaceutical wastewater was 163:4:1. The average effluent TKN concentrations were 49.7 mg/L and 51.2 mg/L for mesophilic and thermophilic UASB reactors, respectively. Moreover, the average effluent TP concentrations were 18.2 mg/L and 19.3 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD:TKN:TP ratios decreased from 163:4:1 to 10:3:1 and 13:2:1 for mesophilic and thermophilic UASB reactors, respectively.

From day 94 to day 145, the UASB reactors were operated at HRT of four days. The average effluent $NH_3$-N of the mesophilic UASB reactor was higher than that of the thermophilic UASB reactor whereas the average effluent $NO_3$-N of the mesophilic UASB reactor was lower than that of the thermophilic reactor. The average $NH_3$-N concentrations increased from 14.9 to 15.1 mg/L and 14.9 to 13.0 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average $NO_3$-N concentrations were relatively constant from 0.3 to 0.4 mg/L and 0.3 to 0.5 mg/L for mesophilic and thermophilic UASB reactors, respectively. At HRT of four days, the UASB reactors were fed by high strength pharmaceutical wastewater (COD 1853-2073 mg/L) and average TP concentrations of pharmaceutical wastewater was 11.3 mg/L. The average effluent TP concentration in mesophilic and thermophilic UASB reactors were 18.1 mg/L and 18.5 mg/L, respectively. The average TKN concentration of pharmaceutical wastewater was 56.7 mg/L, while the average effluent TKN concentrations were 52.2 mg/L and 56.7 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD:TKN:TP ratios decreased

from 180:5:1 to 19:3:1 and 18:3:1 for mesophilic and thermophilic UASB reactors, respectively.

On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The temperature increased to 60°C. From day 111 to day 118, the mesophilic UASB reactor was operated at ambient temperature (24±2°C) while it was being repaired. The effluent $NH_3$-N and $NO_3$-N concentrations ranged from 12.7 to 14.7 mg/L and 0.2 to 0.3 mg/L, respectively. The effluent $NH_3$-N concentrations were lower than the effluent $NH_3$-N concentrations before the mesophilic UASB reactor failed while the effluent $NO_3$-N concentrations relatively did not change, whereas the effluent TP concentrations sharply increased. The effluent TP concentration ranged from 22.4 to 32.5 mg/L. The results for the reactor breakdown period were not included for data analysis. The TKN concentration increased from 57.7 mg/L (influent) to 59.6 mg/L (effluent). After 30 days, the reactor stabilized with effluent TP of 20.5 mg/L

From day 146 to day 179, the UASB reactors were operated at HRT of three days, while for the last 20 days, the UASB reactors were operated at HRT of two days. The average influent $NH_3$-N concentrations were 12.1 mg/L and 11.3 mg/L at HRTs of three and two days, respectively. The average effluent $NH_3$-N concentration in mesophilic UASB reactor decreased at the lower HRT, while in thermophilic UASB reactors it remained constant when the HRT was reduced. The average effluent $NH_3$-N concentrations in mesophilic UASB reactor were 15.4 mg/L and 14.9 mg/L at HRTs of three and two days, respectively whereas in thermophilic UASB reactors, it was 13.7 mg/L at both HRTs of three and two days. The average influent $NO_3$-N concentrations were 0.4 mg/L and 0.5 mg/L at HRTs of three and two days, respectively. The average effluent $NO_3$-N concentrations in both UASB reactors were relatively constant when the HRT was reduced. The average effluent $NO_3$-N concentrations in mesophilic UASB reactor were 0.2 mg/L and 0.3 mg/L at HRTs of three and two days, respectively whereas in thermophilic UASB reactors $NO_3$-N concentrations were 0.4 mg/L and 0.3 mg/L at HRTs of three and two days, respectively.

At HRT of three days the pharmaceutical wastewater COD of 1875 mg/L was fed in UASB reactors, whereas COD of 1820 mg/L was fed to the UASB reactor at HRT of two days. The influent COD:TKN:TP ratio was 158:4:1 for both HRTs of three and two days. The average TKN concentrations of pharmaceutical wastewater were 51.5 mg/L and 49.7 mg/L, whereas the average TP concentrations were 11.7 mg/L and 11.6 mg/L for HRTs of three and two days, respectively. The effluent COD:TKN:TP ratio at HRT of three days were lower than the effluent COD:TKN:TP ratio at HRT of two days in both UASB reactors. This is mainly attributed to the increase in effluent COD as the main factor. The effluent COD:TKN:TP ratios were 24:3:1 and 34:4:1 for HRTs of three and two days in mesophilic reactor, respectively whereas in thermophilic reactor, the effluent COD:TKN:TP ratios were 25:3:1 and 34:3:1 for HRTs of three and two days, respectively. In mesophilic UASB reactor, the average effluent TKN concentration increased from 45.7 to 47.7 mg/L when the HRT was decreased from three to two days while in thermophilic UASB reactor, the average effluent TKN concentration slightly decreased from 48.6 to 48.0 mg/L. Moreover, the average effluent TP concentration in mesophilic UASB reactor decreased from 15.0 to 13.4 mg/L while in thermophilic UASB reactor, the average effluent TP concentration slightly increased from 17.7 to 17.9 mg/L when the HRT was decreased from three to two days.

### 4.2.5 Nutrients in Mesophilic and Thermophilic HUASB Reactors

Figure 4.33 to Figure 4.40 show the influent and effluent nutrient concentrations ($NH_3$-N, $NO_3$-N, TKN and TP) in HUASB reactors. The HUASB reactors started operation 62 days after the UASB reactors. For the first 12 days, the HUASB reactors were fed with low strength wastewater at HRT of three days. The influent $NH_3$-N and $NO_3$-N concentrations ranged from 4.6 to 5.1 mg/L and 0.6 to 0.5 mg/L, respectively. The $NH_3$-N concentrations sharply increased in both HUASB reactors during this study whereas the $NO_3$-N concentrations did not significantly change between the influent and effluent of HUASB reactors. The effluent $NH_3$-N and $NO_3$-N concentrations in mesophilic HUASB reactor varied from 18.4 to 19.4 mg/L and 0.1 to 0.2 mg/L, respectively, while in thermophilic reactor varied from

13.4 to 14.1 mg/L and 0.2 to 0.3 mg/L, respectively at HRT of three days. The influent and effluent $NH_3$-N and $NO_3$-N concentrations in UASB reactors during this study are shown in Figure 4.33 and Figure 4.35, respectively. In low strength pharmaceutical wastewater (COD 503-519 mg/L), the average TKN and TP concentrations of pharmaceutical wastewater were 37.5 mg/L and 6.2 mg/L, respectively. The COD:TKN:TP ratio was 79:6:1. The average effluent TKN concentrations were 31.8 mg/L and 34.1 mg/L for mesophilic and thermophilic HUASB reactors, respectively. Moreover, the average effluent TP concentrations were 26.8 mg/L and 27.2 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average influent and effluent TKN and TP concentrations in HUASB reactors are shown in Figure 4.38 and Figure 4.40, respectively. The COD:TKN:TP ratios decreased from 67:5:1 to 3:1:1 and 11:1:1 for mesophilic and thermophilic HUASB reactors, respectively.

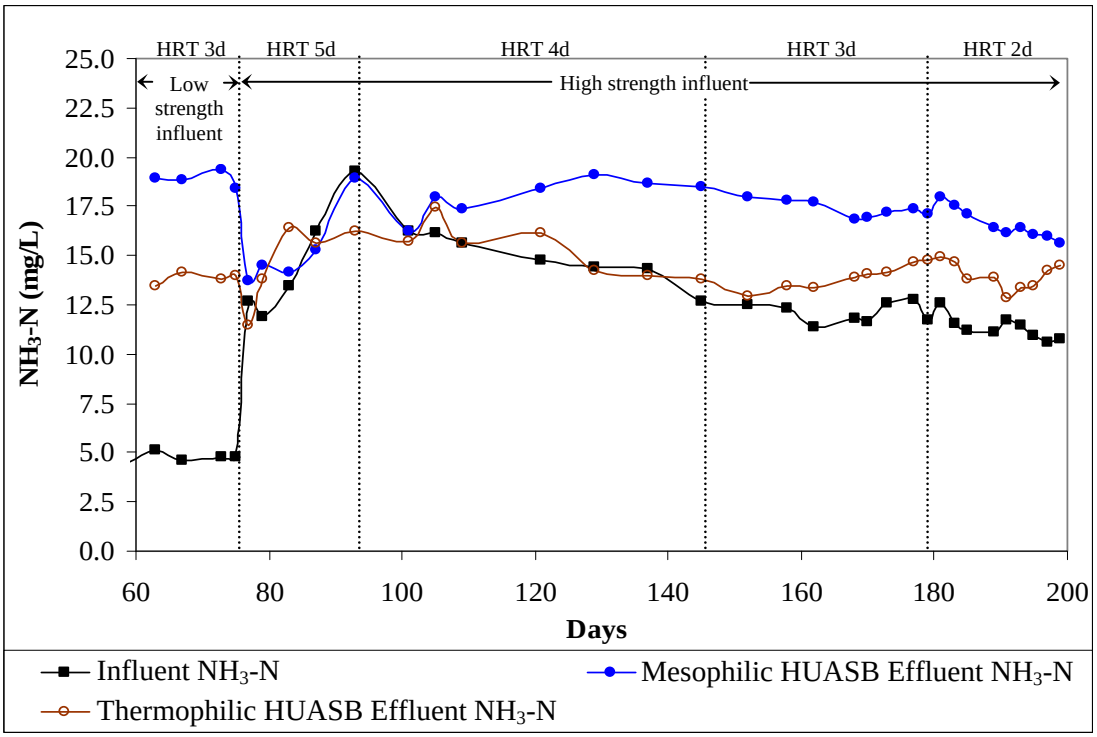


Figure 4.33 Influent and effluent $NH_3$-N concentrations in HUASB reactors

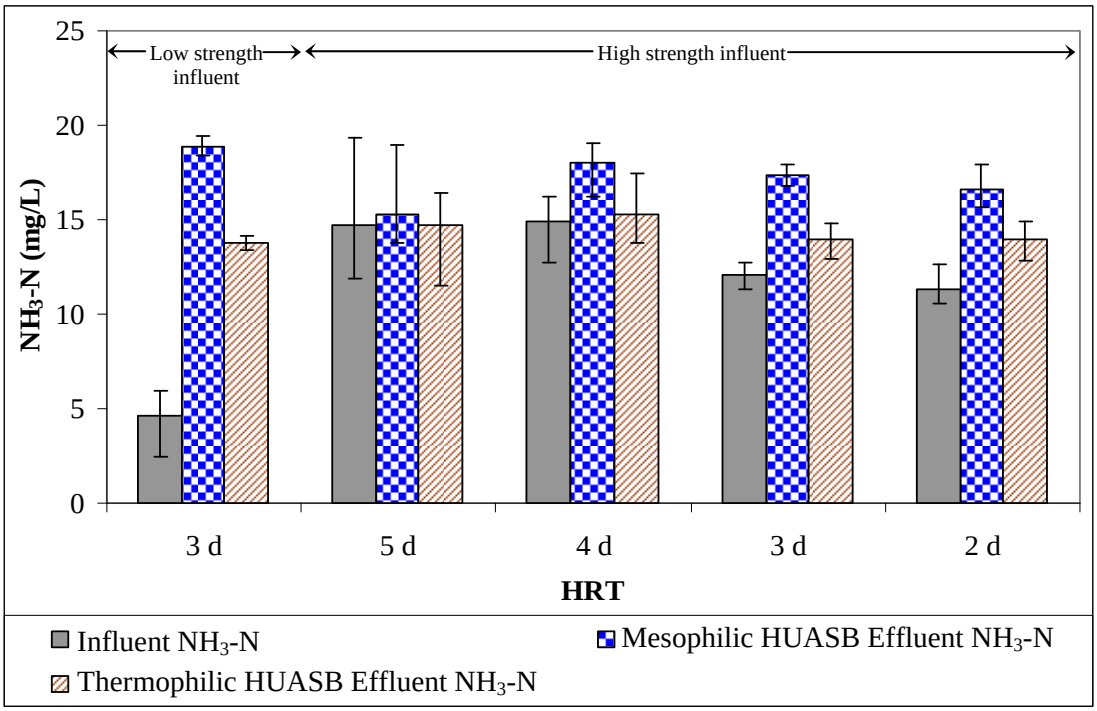


Figure 4.34 Average influent and effluent $NH_3$-N concentrations at each variation of HRT in HUASB reactors

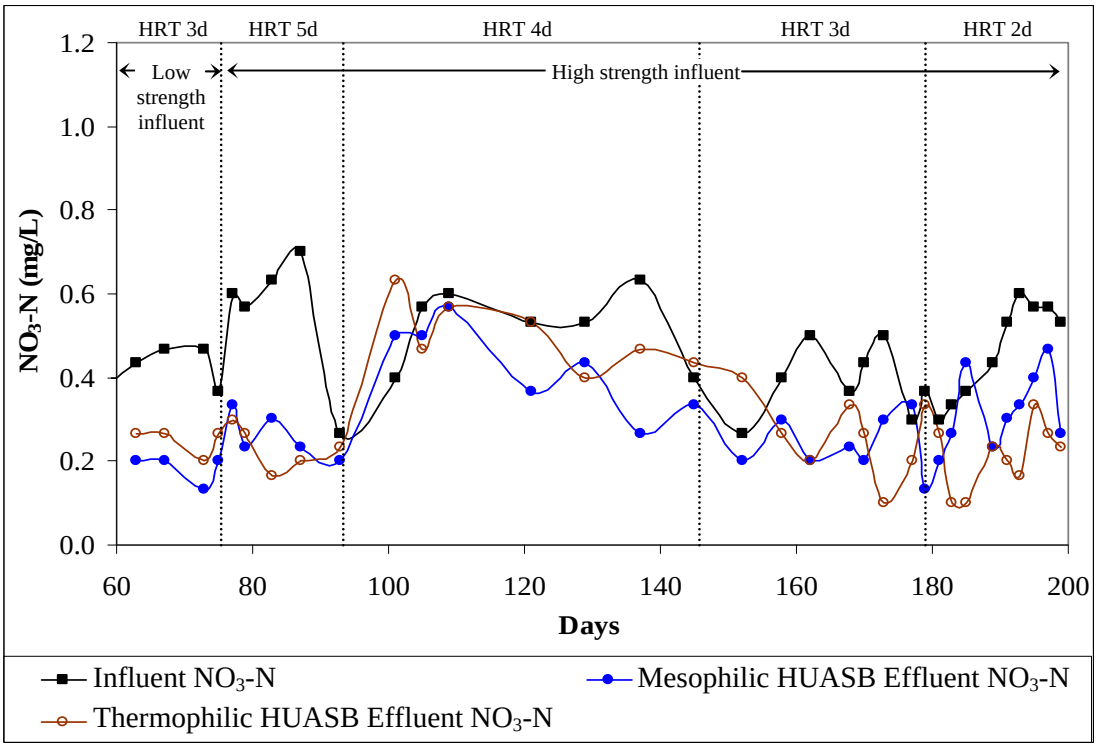


Figure 4.35 Influent and effluent $NO_3$-N concentrations in HUASB reactors

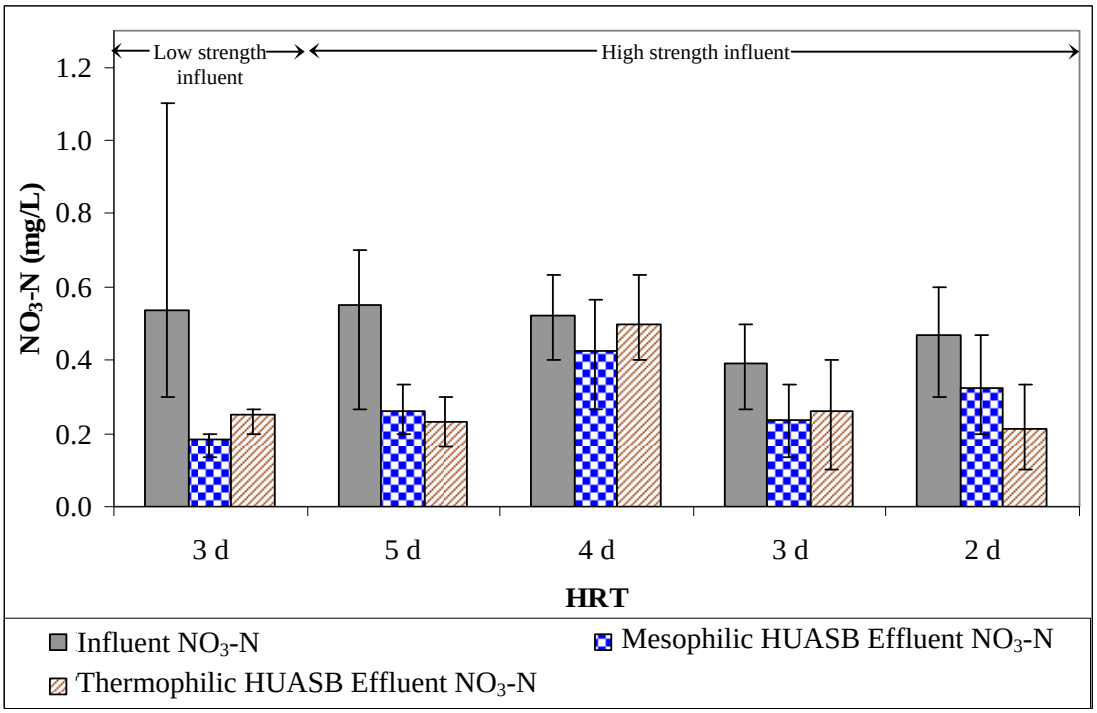


Figure 4.36 Average influent and effluent $NO_3$-N concentrations at each variation of HRT in HUASB reactors

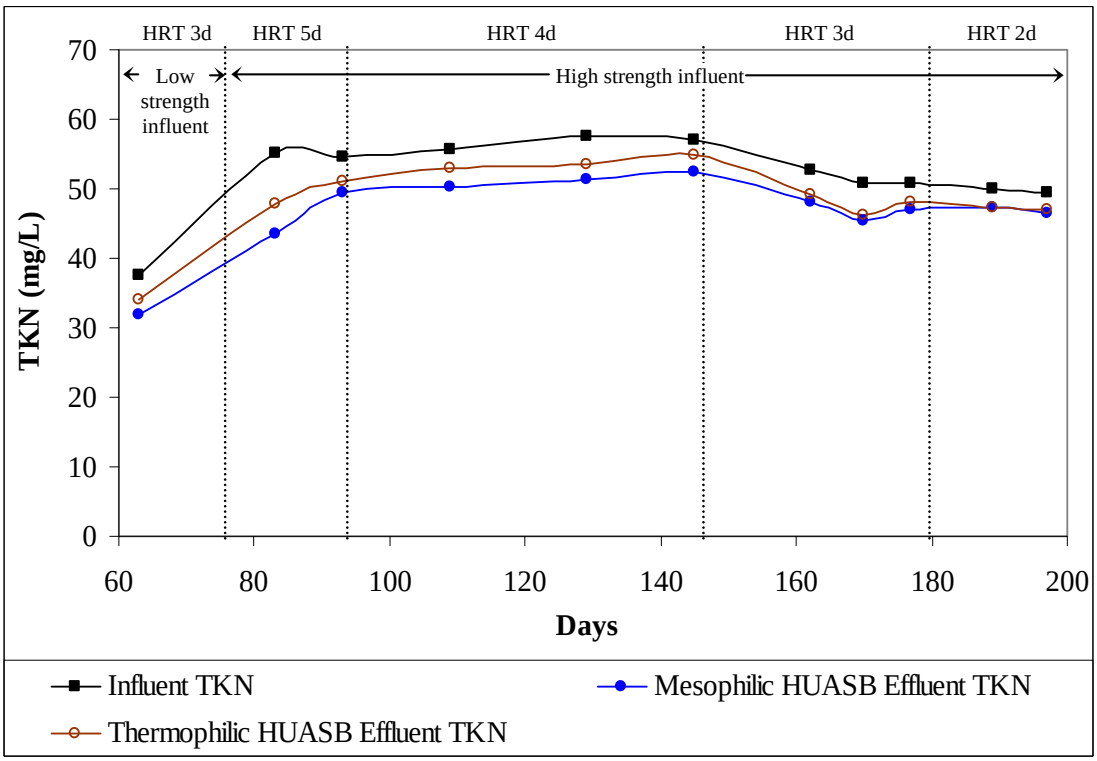


Figure 4.37 Influent and effluent TKN concentrations in HUASB reactors

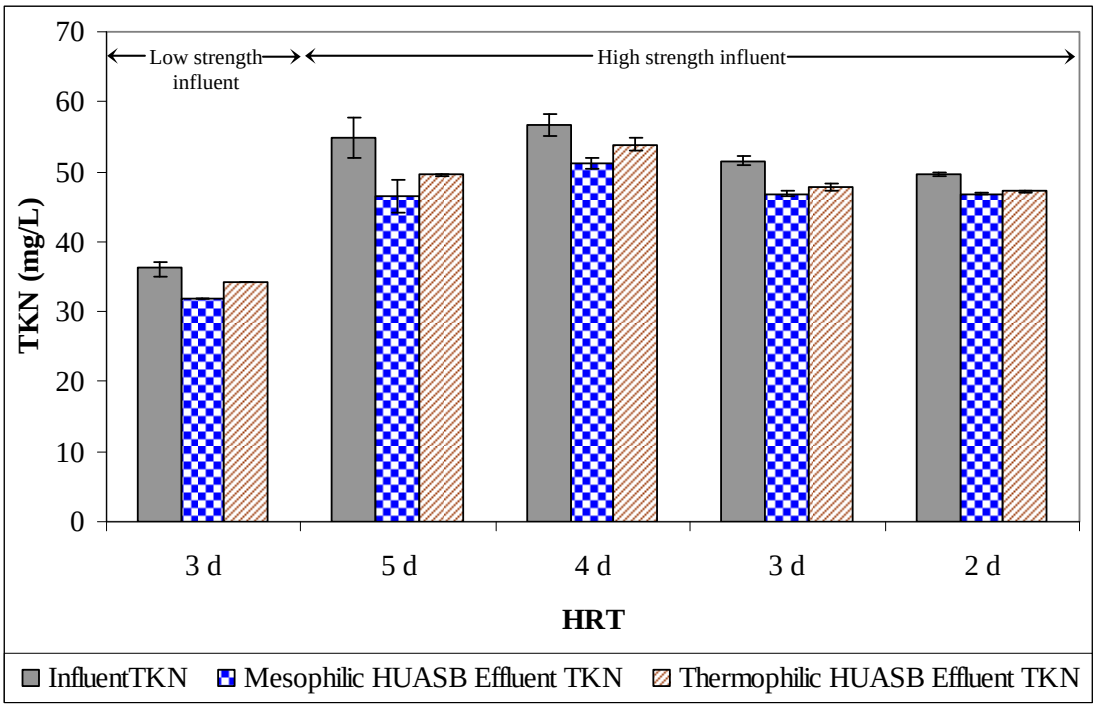


Figure 4.38 Average influent and effluent TKN concentrations at each variation of HRT in HUASB reactors

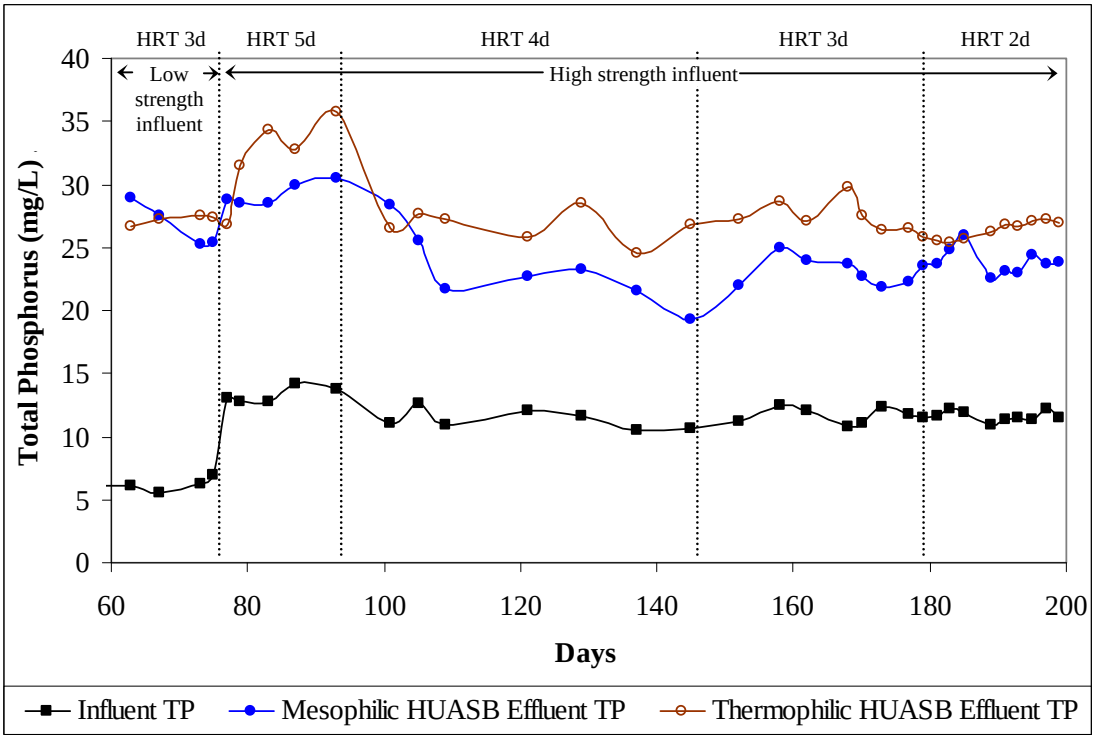


Figure 4.39 Influent and effluent TP concentrations in HUASB reactors

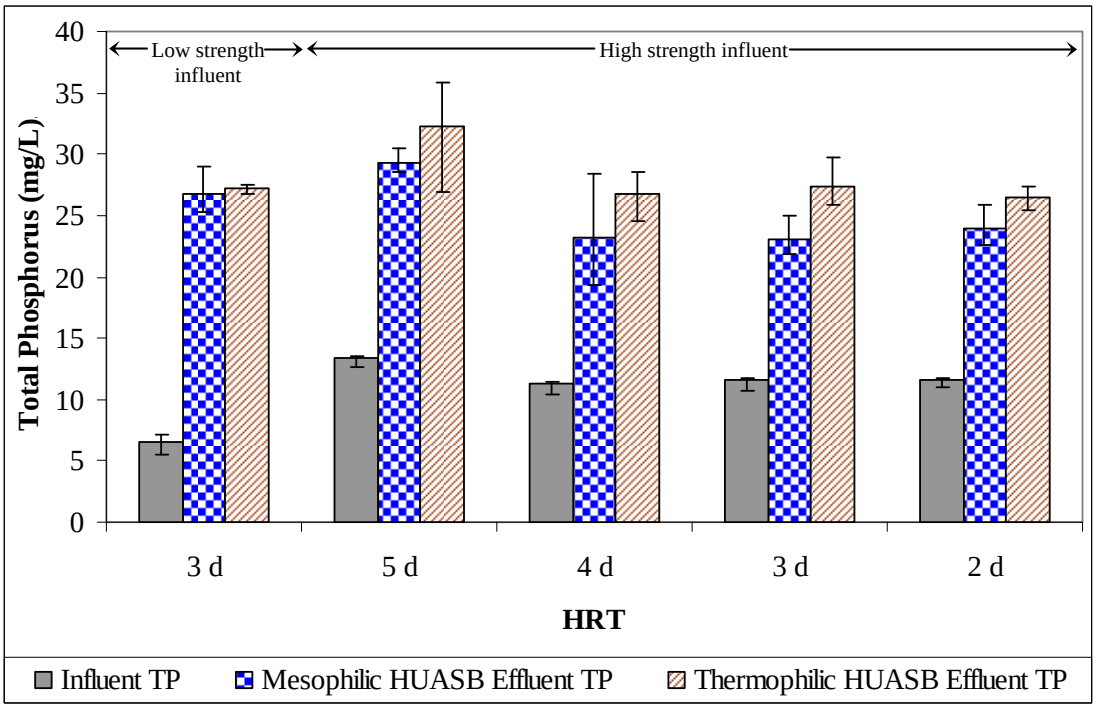


Figure 4.40 Average influent and effluent TP concentrations at each variation of HRT in HUASB reactors

From day 76, high strength wastewater was fed to the HUASB reactors (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. From day 76 to day 93, the HUASB reactors were operated at HRT of five days, while from day 94 to day 145, the HUASB reactors were operated at HRT of four days. The average influent $NH_3$-N concentrations were 14.7 mg/L and 14.9 mg/L at HRT of five and four days, respectively. The average effluent $NH_3$-N concentrations increased in both HUASB reactors when the HRT was reduced. The average effluent $NH_3$-N concentrations in mesophilic HUASB reactor were 15.3 mg/L and 18.0 mg/L at HRTs of five and four days, respectively whereas in thermophilic HUASB reactors, they were 14.7 mg/L and 15.3 mg/L at HRTs of three and two days, respectively. The average influent $NO_3$-N concentrations were 0.6 mg/L and 0.5 mg/L at HRTs of three and two days, respectively. The average effluent $NO_3$-N concentrations in both HUASB reactors were relatively constant when the HRT was reduced. The average effluent $NO_3$-N concentrations in mesophilic HUASB reactor were 0.3 mg/L and 0.4 mg/L at HRTs of three and two days, respectively, whereas in

thermophilic HUASB reactors, they were 0.2 mg/L and 0.5 mg/L at HRTs of three and two days, respectively.

At HRTs of five and four days, the COD concentrations of pharmaceutical wastewater fed to the HUASB reactors were 2127 mg/L and 1989 mg/L, respectively. The influent COD:TKN:TP ratios were 163:4:1 and 180:5:1 for HRTs of five and four days, respectively. The average TKN concentrations of pharmaceutical wastewater were 54.8 mg/L and 56.7 mg/L, whereas the average TP concentrations were 13.3 mg/L and 11.3 mg/L for HRTs of five and four days, respectively. The effluent COD:TKN:TP ratios at HRT of five days were lower than the effluent COD:TKN:TP ratio at HRT of four days in both HUASB reactors. These results are attributed to the increase in effluent COD as the main factor. The effluent COD:TKN:TP ratios were 5:2:1 and 10:4:1 for HRTs of five and four days in mesophilic HUASB reactor, respectively whereas in HUASB thermophilic reactor, the effluent COD:TKN:TP ratios were 8:1:1 and 13:2:1 for HRTs of five and four days, respectively. In mesophilic HUASB reactor, the average effluent TKN concentrations increased from 46.5 to 51.3 mg/L when the HRT was decreased from five to four days while in thermophilic HUASB reactor, the average effluent TKN concentrations increased from 49.5 to 53.8 mg/L. Moreover, the average effluent TP concentrations in mesophilic HUASB reactor decreased from 29.3 to 23.2 mg/L while in thermophilic HUASB reactor, the average effluent TP concentrations decreased from 32.2 to 26.7 mg/L when the HRT was decreased from five to four days.

From day 146 to day 179, the HUASB reactors were operated at HRT of three days and fed by the pharmaceutical wastewater COD of 1875 mg/L, while for the last 20 days, the UASB reactors were operated at HRT of two days and supplied by the pharmaceutical wastewater with COD of 1820 mg/L. At HRT of three days, the average TKN and TP concentrations of pharmaceutical wastewater were 51.5 mg/L and 11.7 mg/L, respectively, whereas at HRT of two days, the average TKN and TP concentrations were 49.7 mg/L and 11.6 mg/L, respectively. In mesophilic HUASB reactor, the average effluent TKN concentrations were about the same

(46.8 mg/L and 46.9 mg/L) when the HRT was decreased from three to two days while in thermophilic HUASB reactor, the average TKN concentration slightly decreased from 47.8 mg/L to 47.2 mg/L. Moreover, the average effluent TP concentration in mesophilic HUASB reactor increased from 23.1 to 23.9 mg/L, while in thermophilic HUASB reactor, the average effluent TP concentration decreased from 27.4 to 26.4 mg/L when the HRT was decreased from three to two days. The influent COD:TKN:TP ratios were 158:4:1 for both HRTs of three and two days. The effluent COD:TKN:TP ratios at HRT of two days were higher than the effluent COD:TKN:TP ratios at HRT of three days in both HUASB reactors. The effluent COD:TKN:TP ratios were 12:2:1 and 15:2:1 for HRTs of three and two days in mesophilic HUASB reactor, respectively whereas in thermophilic HUASB reactor, the effluent COD:TKN:TP ratios were 14:2:1 and 17:2:1 for HRTs of three and two days, respectively.

The average influent $NH_3$-N concentrations were 12.1 mg/L and 11.3 mg/L at HRTs of three and two days, respectively. In mesophilic HUASB reactor, the average effluent $NH_3$-N concentrations decreased and in thermophilic HUASB reactor was constant, when the HRT was reduced. The average effluent $NH_3$-N concentrations in mesophilic HUASB reactor were 17.4 mg/L and 16.6 mg/L at HRTs of three and two days, respectively whereas in thermophilic HUASB reactors were 13.9 mg/L and 14.0 mg/L at HRTs of three and two days, respectively. The average influent $NO_3$-N concentrations were 0.4 mg/L and 0.5 mg/L at HRTs of three and two days, respectively. The average effluent $NO_3$-N concentrations in both HUASB reactors were relatively constant when the HRT was reduced. The average effluent $NO_3$-N concentrations in mesophilic HUASB reactor were 0.2 mg/L and 0.3 mg/L at HRTs of three and two days, respectively whereas in thermophilic HUASB reactors were 0.3 mg/L and 0.2 mg/L at HRTs of three and two days, respectively.

### 4.2.6 Summary of Nutrient Parameters in UASB and HUASB Reactors

Table 4.1 to Table 4.6 show the average nutrient concentrations ($NH_3$-N, $NO_3$-N, TKN and TP) in UASB and HUASB reactors at steady state conditions. The

concentration of $NH_3$-N and total phosphorous increased during this study, whereas the concentration of $NO_3$-N was constant and concentration of TKN slightly reduced. Jenicek et al. (1996) also reported negligible nitrogen removal using a UASB reactor treating biosynthetic pharmaceutical wastewater.

Table 4.3 Average influent and effluent $NH_3$-N concentrations in UASB and HUASB reactors

| HRT (days) | Influent $NH_3$-N (mg/L) | Effluent $NH_3$-N (mg/L) | | | |
|---|---|---|---|---|---|
| | | Mesophilic UASB | Thermophilic UASB | Mesophilic HUASB | Thermophilic HUASB |
| Low strength influent | | | | | |
| 5 | 3.3 | 12.5 | 11.6 | N/A | N/A |
| 3 | 4.6 | 8.7 | 7.2 | 18.9 | 13.8 |
| High strength influent | | | | | |
| 5 | 14.7 | 19.2 | 12.7 | 15.3 | 14.7 |
| 4 | 14.9 | 15.1 | 13.0 | 18.0 | 15.3 |
| 3 | 12.1 | 15.4 | 13.7 | 17.4 | 13.9 |
| 2 | 11.3 | 14.9 | 13.7 | 16.6 | 14.0 |

Table 4.4 Average influent and effluent $NO_3$-N concentrations in UASB and HUASB reactors

| HRT (days) | Influent $NO_3$-N (mg/L) | Effluent $NO_3$-N (mg/L) | | | |
|---|---|---|---|---|---|
| | | Mesophilic UASB | Thermophilic UASB | Mesophilic HUASB | Thermophilic HUASB |
| Low strength influent | | | | | |
| 5 | 0.7 | 0.6 | 0.3 | N/A | N/A |
| 3 | 0.5 | 0.4 | 0.6 | 0.2 | 0.3 |
| High strength influent | | | | | |
| 5 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 |
| 4 | 0.5 | 0.3 | 0.4 | 0.4 | 0.5 |
| 3 | 0.4 | 0.2 | 0.4 | 0.2 | 0.3 |
| 2 | 0.5 | 0.3 | 0.3 | 0.3 | 0.2 |

Table 4.5 Average influent and effluent TKN concentrations in UASB and HUASB reactors

| HRT (days) | Influent TKN (mg/L) | Effluent TKN (mg/L) | | | |
|---|---|---|---|---|---|
| | | Mesophilic UASB | Thermophilic UASB | Mesophilic HUASB | Thermophilic HUASB |
| Low strength influent | | | | | |
| 5 | 36.9 | 33.3 | 34.6 | N/A | N/A |
| 3 | 36.3 | 33.1 | 34.0 | 31.8 | 34.1 |
| High strength influent | | | | | |
| 5 | 54.8 | 49.7 | 51.2 | 46.5 | 49.5 |
| 4 | 56.7 | 52.2 | 54.0 | 51.3 | 53.8 |
| 3 | 51.5 | 45.7 | 48.6 | 46.8 | 47.8 |
| 2 | 49.7 | 47.7 | 48.0 | 46.9 | 47.2 |

Table 4.6 Average influent and effluent TP concentrations in UASB and HUASB reactors

| HRT (days) | Influent TP (mg/L) | Effluent TP (mg/L) | | | |
|---|---|---|---|---|---|
| | | Mesophilic UASB | Thermophilic UASB | Mesophilic HUASB | Thermophilic HUASB |
| Low strength influent | | | | | |
| 5 | 6.6 | 17.3 | 19.9 | N/A | N/A |
| 3 | 6.6 | 18.1 | 20.8 | 26.8 | 27.2 |
| High strength influent | | | | | |
| 5 | 13.3 | 18.2 | 19.3 | 29.3 | 32.2 |
| 4 | 11.3 | 18.1 | 18.5 | 23.2 | 26.7 |
| 3 | 11.7 | 15.0 | 17.7 | 23.1 | 27.4 |
| 2 | 11.6 | 13.4 | 17.9 | 23.9 | 26.4 |

The effluent from the UASB reactor contained higher orthophosphates and nitrogen levels. Under anaerobic conditions, phosphorous accumulating organisms (PAOs) will assimilate fermentation products into storage products within the cells with concomitant release of phosphorous from stored polyphosphates. The nitrogen demand for growth of anaerobic bacteria is almost negligible and if no accumulation of organic matter in the bioreactor occurs, the balance between total nitrogen flow in and out of the reactor should be constant (Metcalf & Eddy, 2003; Parawira et al., 2005). The effluent $NH_3$-N concentration increased and the effluent $NO_3$-N concentration was constant because nitrification did not occur in UASB and HUASB reactors.

## 4.3 VFA, alkalinity and pH in UASB and HUASB Reactors

The anaerobic reactors generally are affected by the changing of environmental and/or operating conditions. The typical responses in the anaerobic reactor include a decrease in performance, VFA accumulation, pH and alkalinity drop, change of biogas production and composition and sludge washout. The VFA/alkalinity ratio should be lower than 0.3 (Leitao et al., 2006).

During this study, the pH of pharmaceutical wastewater ranged from 4.76 to 6.04. The influent alkalinity was maintained at 1500 to 2000 mg $CaCO_3$/L. The pH of pharmaceutical wastewater after adjustment with sodium bicarbonate was approximately 7.48. The influent and effluent pH and alkalinity in UASB and

HUASB reactors during this study are shown in Figure 4.41 and Figure 4.42, respectively.

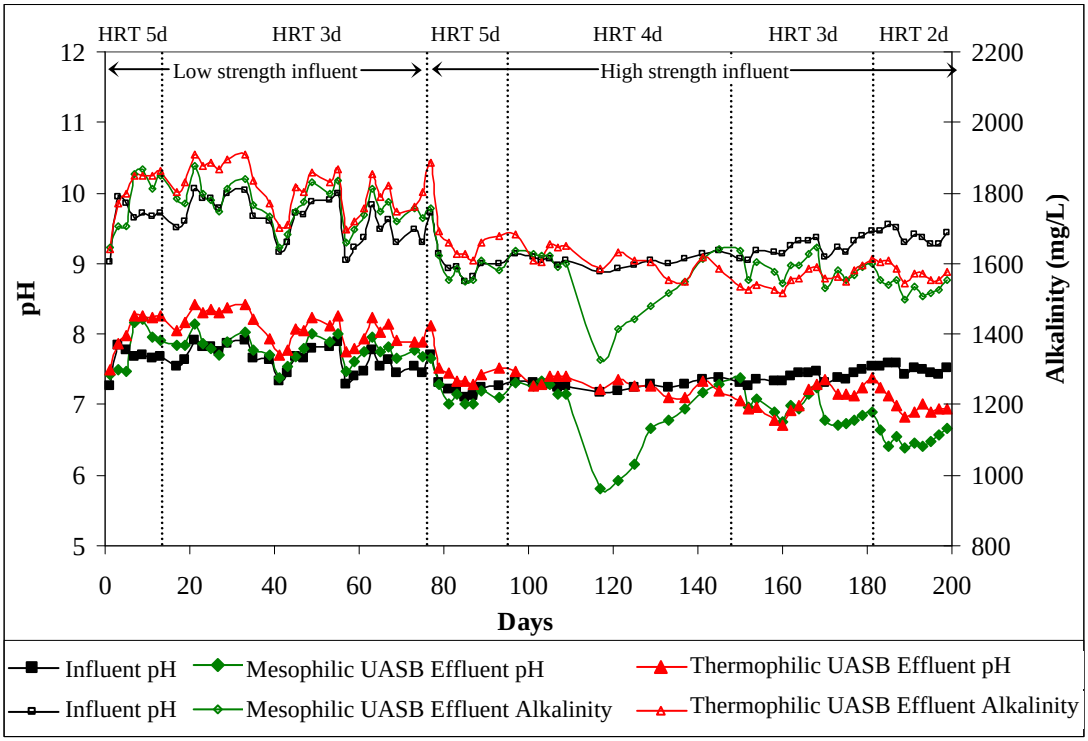


Figure 4.41 Influent and effluent pH and alkalinity in UASB reactors

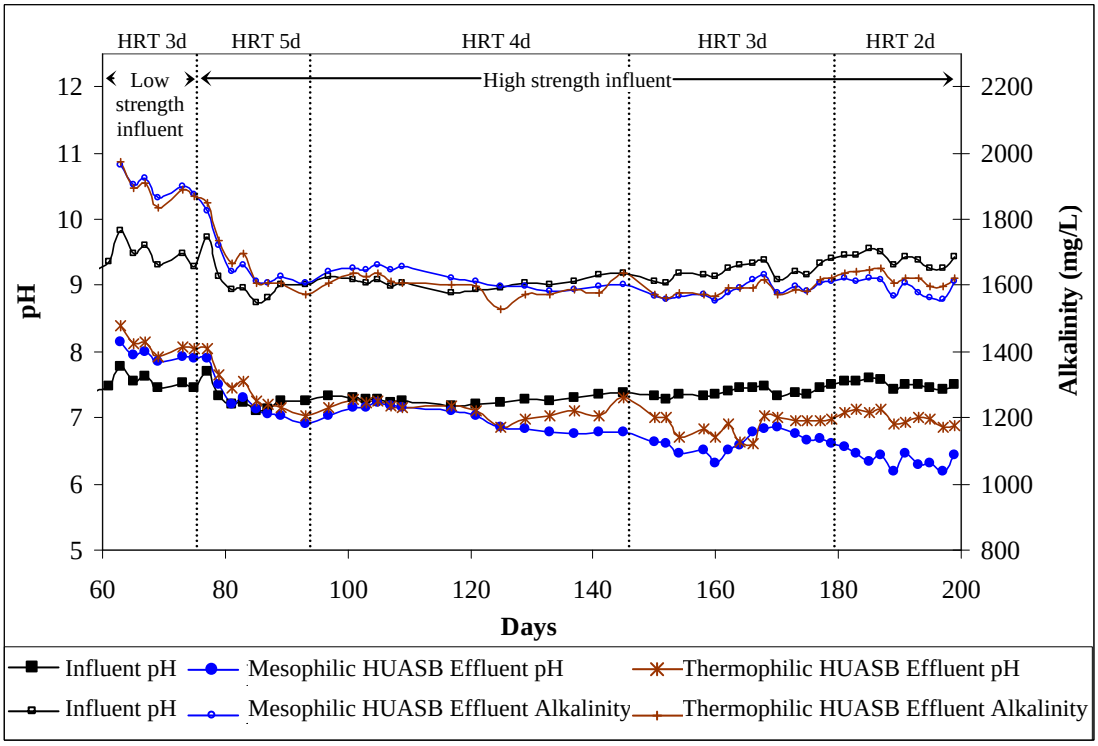


Figure 4.42 Influent and effluent pH and alkalinity in HUASB reactors

In the first 75 days, the UASB reactors were fed with low strength influent (COD 458-526 mg/L) at HRTs of five and three days. The influent pH of the UASB reactors ranged from 7.26 to 7.84 and 7.28 to 7.91, whereas, the influent alkalinity ranged from 1603 to 1787 mg $CaCO_3$/L and 1609 to 1813 mg $CaCO_3$/L for HRT of five and three days, respectively. The average effluent pH slightly decreased when the HRT was decreased from five to three days. The average effluent pH decreased from 7.81 to 7.78 and 8.25 to 7.98 for mesophilic and thermophilic UASB reactors, respectively. The effluent alkalinity at HRT of five days ranged from 1644 to 1866 mg $CaCO_3$/L and 1848 to 1861 mg $CaCO_3$/L, whereas at HRT of three days, the effluent alkalinity ranged from 1646 to 1875 mg $CaCO_3$/L and 1696 to 1909 mg $CaCO_3$/L for mesophilic and thermophilic UASB reactors, respectively.

The HUASB reactors were put in operation 62 days after the UASB reactors. For the first 12 days, the HUASB reactors were fed with low strength wastewater at HRT of three days. The average effluent pH were 7.95 and 8.05, whereas the effluent alkalinity ranged from 1865 to 1964 mg $CaCO_3$/L and 1833 to 1973 mg $CaCO_3$/L for mesophilic and thermophilic HUASB reactors, respectively.

The VFA was measured from day 65 and the average influent and effluent VFA concentration in UASB and HUASB reactors during this study is shown in Figure 4.43. At HRT of three days, the average influent VFA was 16.2 mg acetic acid/L. The average effluent VFA in mesophilic reactors was lower than the average effluent VFA in thermophilic reactors. The average effluent VFA in mesophilic and thermophilic UASB reactors were 23.5 mg acetic acid/L and 36.5 mg acetic acid/L, respectively, whereas the average effluent VFA were 29.0 mg acetic acid/L and 55.3 mg acetic acid/L for mesophilic and thermophilic HUASB reactors, respectively.

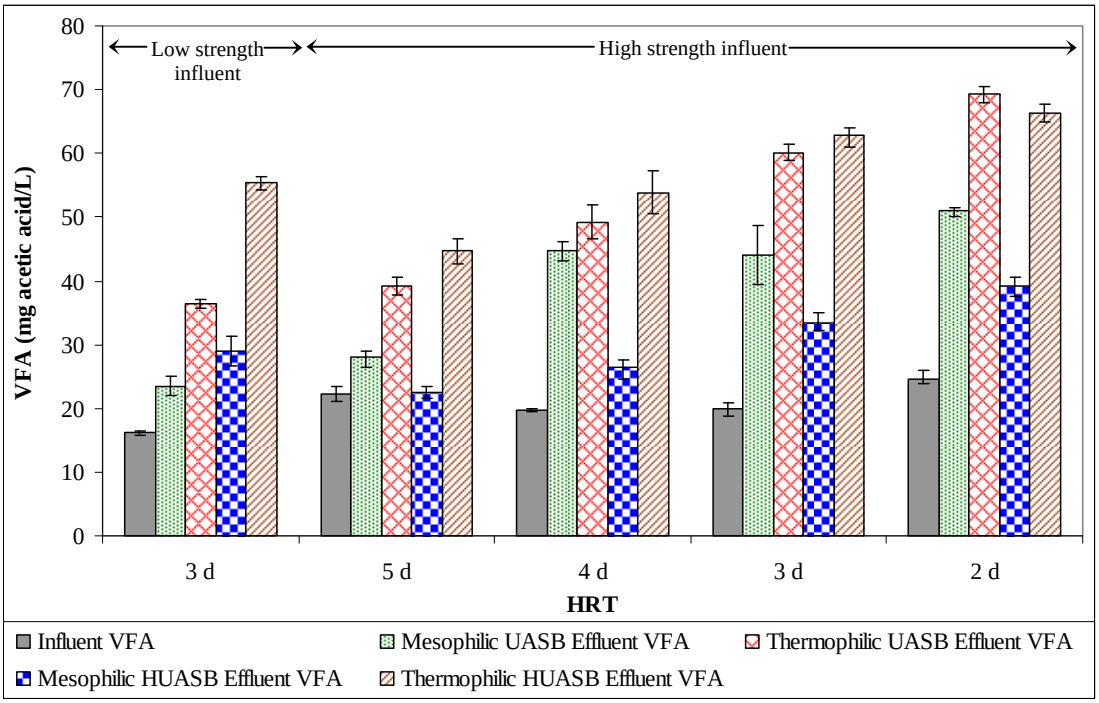


Figure 4.43 Average influent and effluent VFA concentrations in UASB and HUASB reactors

From day 76 to day 199, the UASB and HUASB reactors were fed with high strength wastewater (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. The influent pH and alkalinity in UASB reactors ranged from 7.11 to 7.70 mg $CaCO_3$/L and 1547 to 1743 mg $CaCO_3$/L, respectively. On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The effluent VFA sharply increased from 35 to 293 mg acetic acid/L, whereas the effluent pH sharply decreased from 7.16 to 5.81. The pH and alkalinity in the reactor during the upset period was not included in data analysis. After 30 days, the reactor stabilized with pH of 7.28 and alkalinity of 1643 mg $CaCO_3$/L.

The average effluent pH decreased when the HRT were decreased. The average effluent pH in mesophilic UASB reactor was lower than the average effluent pH in thermophilic UASB reactor. The average effluent pH in mesophilic UASB reactor were 7.18, 7.26, 6.89 and 6.55, whereas in thermophilic UASB reactor, the average effluent pH were 7.50, 7.29, 7.16 and 6.92 at HRTs of five, four, three and two days, respectively. The average effluent alkalinity also decreased when the HRT were

decreased in both of UASB reactors. The average effluent alkalinity in mesophilic UASB reactor were 1600, 1621, 1582 and 1537 mg $CaCO_3$/L, whereas in thermophilic UASB reactor, the average effluent alkalinity were 1680, 1613, 1570 and 1562 mg $CaCO_3$/L at HRTs of five, four, three and two days, respectively. The average effluent alkalinity in mesophilic UASB reactor was higher than the average effluent alkalinity in thermophilic UASB reactor at HRTs of four and three days. It seems the reactor was still sensitive due to its previous failure (temperature shock).

The average effluent pH in mesophilic HUASB reactor was lower than the average effluent pH in thermophilic HUASB reactor. The average effluent pH in mesophilic HUASB reactor were 7.25, 6.99, 6.63 and 6.36, whereas in thermophilic HUASB reactor, the average effluent pH were 7.42, 7.12, 6.86 and 6.86 at HRTs of five, four, three and two days, respectively. The average effluent alkalinity also decreased when the HRT were decreased in both of HUASB reactors. The average effluent alkalinity in mesophilic HUASB reactor were 1663, 1621, 1587 and 1595 mg $CaCO_3$/L, whereas in thermophilic HUASB reactor, the average effluent alkalinity were 1668, 1597, 1592 and 1624 mg $CaCO_3$/L at HRTs of five, four, three and two days, respectively.

The VFA of high strength influent ranged from 15.7 to 25.3 mg acetic acid/L. At HRT of five days, the average effluent VFA in mesophilic reactors were lower than the average effluent VFA in thermophilic reactors at both UASB and HUASB reactors. The average VFA in mesophilic and thermophilic UASB reactors were 28.0 mg acetic acid/L and 39.2 mg acetic acid/L, respectively, whereas the average VFA were 22.5 mg acetic acid/L and 44.7 mg acetic acid/L for mesophilic and thermophilic HUASB reactors, respectively. The average effluent VFA increased in all reactors when the HRT were decreased, except in mesophilic UASB reactor after it failure. The average effluent VFA increased from 49.3 to 60.2 mg acetic acid/L, 26.5 to 33.3 mg acetic acid/L and 53.8 to 62.8 mg acetic acid/L for thermophilic UASB reactor, the mesophilic and thermophilic HUASB reactors, respectively, when the HRT was decreased from four to three days. Whereas, the average effluent VFA decreased from 44.7 to 44.1 mg acetic acid/L in mesophilic UASB reactor. For the

last 20 days, the reactors were operated at HRT of two days. The average effluent VFA were 51.0, 69.3, 39.2, 66.3 mg acetic acid/L for mesophilic and thermophilic UASB reactors and mesophilic and thermophilic HUASB reactors, respectively.

In their review, Leitao et al. (2006) reported that methanogenic activity optimally proceed in the pH range of 6.3-7.8. They also reported that the effect of a drastic pH changed in the influent depended on the alkalinity availability in the anaerobic reactor. This behavior occurred because the buffer capacity of the anaerobic reactor sufficed to maintain the pH in the anaerobic reactor in the optimal range. The recovery in the anaerobic process depends on the level and duration of the imposed changed, in addition to the concentration of VFA during the event. The VFA concentrations in the effluent of all reactors were low and the total alkalinity was relatively high. Accordingly, the VFA/bicarbonate alkalinity ratio was always less than 0.3.

## 4.4 Kinetic Evaluation

Kinetic evaluation is important in the design, development and operation of UASB and HUASB reactors (Bhunia and Ghangrekar, 2008; Buyukkamaci and Filibeli, 2002). The determination of kinetics constants of the reactors was performed by applying three kinetic models to data obtained from the experiments. Based on the biochemistry and microbiology in the anaerobic process, kinetic evaluation deals with operational and environmental factors. Bacterial growth kinetics was based on two fundamental relationships, i.e., growth rate and substrate utilization rate. Various kinetic models reported for biological treatment (including for anaerobic treatment) predominantly based on Monod's equation or its modifications. Different researchers have determined the values of kinetic coefficients by means of regression analysis of experimental data that were generated from lab scale and/or pilot scale studies. Based on previous studies, most kinetic models were non-linear in nature. Therefore, a non-linear regression technique would be more suitable for evaluation of kinetic constants embedded in the models. However, linear regression can also able to yield a set of good estimates, if the non-linear model could be transformed into proper linear form. Three kinetic models i.e. Monod, modified Stover-Kincannon and Grau second-order

were applied in this study and the reactor performance data under steady-state condition for kinetic models analysis are shown in Table 4.7. Monod and modified Stover-Kincannon kinetic models were evaluated for high strength wastewater, whereas Grau second-order kinetic model was evaluated for low strength and high strength wastewater. Due to low $R^2$ values, the low strength wastewater data was not used in Monod and Stover-Kincannon kinetic models.

The sludge volume and sludge concentration in UASB and HUASB reactors during this study are shown in Figure 4.44 and Figure 4.45, respectively. In the first 75 days, the UASB reactors were fed with low strength influent at HRTs of five and three days. At HRT of five days, the average sludge volumes were 2.42 L and 2.39 L, whereas the average sludge concentrations were 13558 mg VSS/L and 12245 mg VSS/L for mesophilic and thermophilic UASB reactors, respectively. At HRT of three days, the average sludge concentrations were 13922 mg VSS/L and 12914 mg VSS/L and the sludge volumes increased from 2.42 to 2.43 L and 2.39 to 2.40 L for mesophilic and thermophilic UASB reactors, respectively. The HUASB reactors were put in operation 62 days after the UASB reactors. For mesophilic and thermophilic HUASB reactors, the average sludge volumes were 2.36 L and 2.29 L, whereas the average sludge concentrations were 14124 mg VSS/L and 13098 mg VSS/L, respectively.

From day 76 to day 199, the UASB and HUASB reactors were fed with high strength wastewater at HRTs of five, four, three and two days. For mesophilic and thermophilic UASB reactors at HRT of five days, the average sludge volumes were 2.43 L and 2.40 L, whereas the average sludge concentrations were 14438 mg VSS/L and 13668 mg VSS/L, respectively, whereas for mesophilic and thermophilic HUASB reactors, the sludge volumes and concentrations were 2.37 L and 2.31 L and 14736 mg VSS/L and 13428 mg VSS/L, respectively. On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The sludge volume and sludge concentration decreased from 2.43 to 2.39 L and 14959 to 12927 mg VSS/L, respectively, due to sludge washout. The sludge data in the reactor during the upset

period was not included in data analysis. After 30 days, the reactor stabilized with sludge volume of 2.37 L and sludge concentration of 13551 mg VSS/L.

Table 4.7 Reactor performance parameters under steady-state condition

| HRT (day) | Influent COD (mg/L) | Effluent COD (mg/L) | Sludge bed volume (L) | X (mg/L) | Xe (mg/L) | Influent flow rate (L/day) | SRT (day) |
|---|---|---|---|---|---|---|---|
| Mesophilic UASB | | | | | | | |
| 5* | 487 | 60 | 2.42 | 13558 | 15 | 1.00 | 2218 |
| 3* | 505 | 65 | 2.42 | 13922 | 10 | 1.67 | 1971 |
| 5 | 2127 | 158 | 2.43 | 14438 | 16 | 1.00 | 2248 |
| 4 | 1989 | 262 | 2.41 | 14424 | 17 | 1.25 | 1597 |
| 3 | 1875 | 369 | 2.37 | 15452 | 21 | 1.67 | 1057 |
| 2 | 1820 | 478 | 2.39 | 16545 | 26 | 2.50 | 614 |
| Thermophilic UASB | | | | | | | |
| 5* | 487 | 95 | 2.39 | 12245 | 12 | 1.00 | 2391 |
| 3* | 505 | 83 | 2.39 | 12914 | 13 | 1.67 | 1449 |
| 5 | 2127 | 213 | 2.40 | 13668 | 19 | 1.00 | 1759 |
| 4 | 1989 | 329 | 2.42 | 14216 | 30 | 1.25 | 913 |
| 3 | 1875 | 464 | 2.43 | 15652 | 24 | 1.67 | 936 |
| 2 | 1820 | 582 | 2.43 | 16701 | 27 | 2.50 | 596 |
| Mesophilic HUASB | | | | | | | |
| 3* | 505 | 61 | 2.36 | 14124 | 12 | 1.67 | 1647 |
| 5 | 2127 | 133 | 2.36 | 14736 | 14 | 1.00 | 2534 |
| 4 | 1989 | 208 | 2.38 | 15248 | 15 | 1.25 | 1952 |
| 3 | 1875 | 270 | 2.39 | 16530 | 19 | 1.67 | 1261 |
| 2 | 1820 | 319 | 2.40 | 17412 | 21 | 2.50 | 793 |
| Thermophilic HUASB | | | | | | | |
| 3* | 505 | 172 | 2.29 | 13098 | 15 | 1.67 | 1205 |
| 5 | 2127 | 281 | 2.30 | 13428 | 18 | 1.00 | 1816 |
| 4 | 1989 | 366 | 2.32 | 14263 | 21 | 1.25 | 1304 |
| 3 | 1875 | 382 | 2.33 | 15643 | 21 | 1.67 | 1062 |
| 2 | 1820 | 504 | 2.33 | 16493 | 24 | 2.50 | 638 |

(* low strength wastewater data for Grau second-order kinetic model)

($X$ is the biomass concentration in the sludge bed; $X_e$ is the biomass concentration of effluent wastewater)

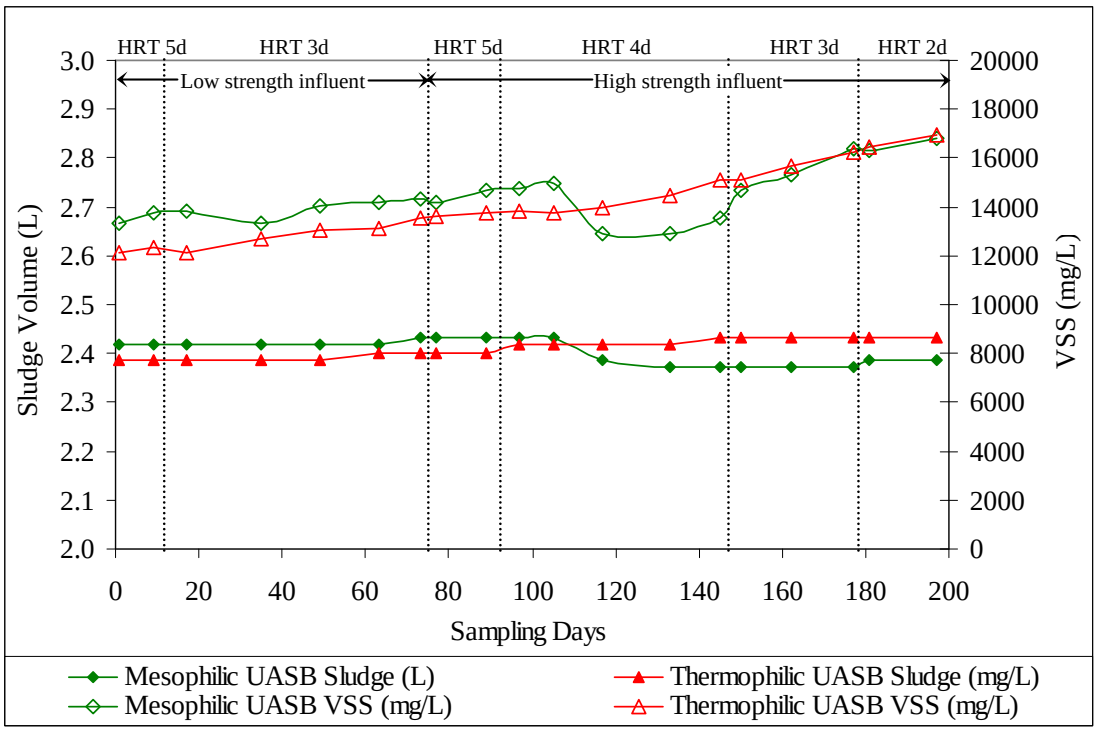


Figure 4.44 Sludge volume and sludge concentration in UASB reactors

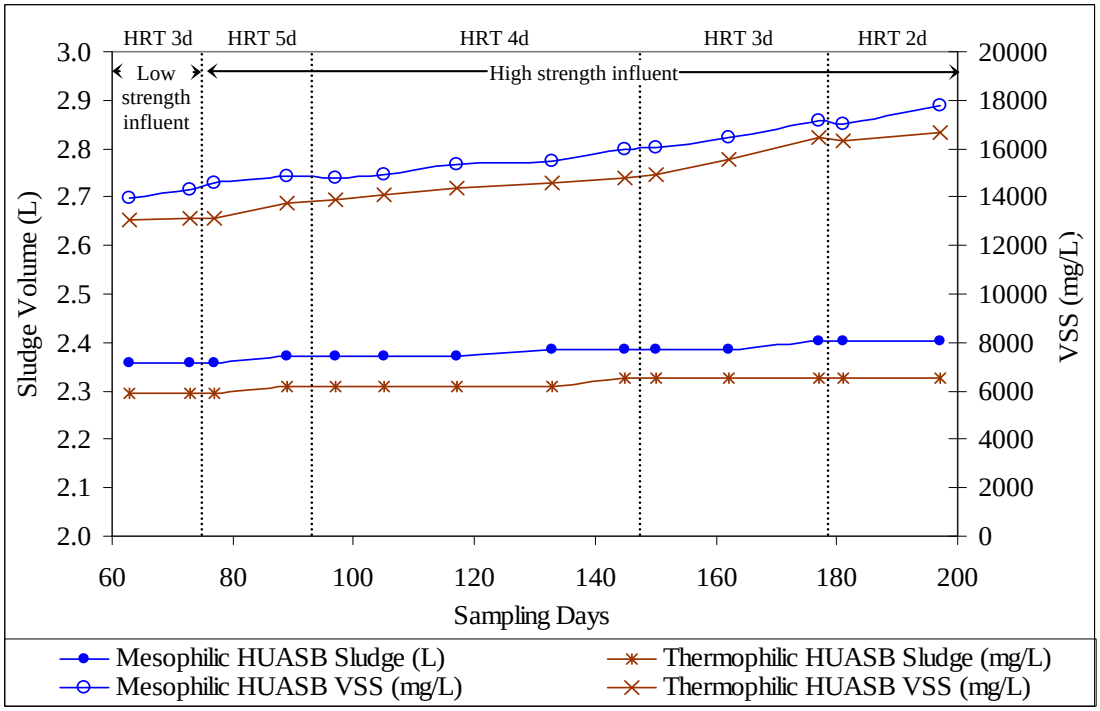


Figure 4.45 Sludge volume and sludge concentration in HUASB reactors

At HRT of four days, the sludge volumes were increased in all reactors, except in mesophilic UASB reactor. The sludge volume increased from 2.42 to 2.43 L, 2.37 to 2.39 L and 2.31 to 2.33 L for thermophilic UASB, mesophilic and thermophilic HUASB reactors, respectively. The average sludge concentration in thermophilic UASB reactor was 14216 mg VSS/L, whereas in the mesophilic and thermophilic HUASB reactors it was 15248 mg VSS/L and 14263 mg VSS/L respectively. The average sludge volumes and sludge concentrations in mesophilic UASB reactors were 2.41 L and 14424 mg VSS/L, respectively.

From day 146 to day 199, the reactors were operated at HRTs of three and two days. In mesophilic UASB reactor, the sludge volume increased from 2.37 to 2.39 L, whereas it was constant in thermophilic UASB reactor. The average sludge concentrations increased from 15452 to 16545 mg VSS/L and 15652 to 16701 mg VSS/L for mesophilic and thermophilic UASB reactors, respectively. In mesophilic HUASB reactor, the sludge volume also increased from 2.39 to 2.40 L, whereas it was constant in thermophilic HUASB reactor. The average sludge concentrations increased from 16530 to 17412 mg VSS/L and 15643 to 16493 mg VSS/L for mesophilic and thermophilic HUASB reactors, respectively.

### 4.4.1 Application of Monod Kinetic Model

For the UASB and HUASB reactors without biomass recycle, the rate of change of biomass and substrate in the system can be expressed respectively as Eqs. 4.1 and 4.2:

$$\frac{dX}{dt} = \frac{Q}{V_b} \cdot X_o - \frac{Q}{V_b} \cdot X_e + \mu \cdot X - K_d \cdot X \qquad (4.1)$$

(Wiesmann et al., 2007)

$$\frac{dS}{dt} = \frac{Q}{V_b} \cdot S_o - \frac{Q}{V_b} \cdot S_e - \frac{\mu \cdot X}{Y} \qquad (4.2)$$

(Wiesmann et al., 2007)

where, $Q$ is the flow rate of influent wastewater in L/day; $V_b$ is the volume of sludge bed in L; $X_o$ is the biomass concentration of influent wastewater in mg/L; $X_e$ is the biomass concentration of effluent wastewater in mg/L; $X$ is the biomass concentration

in the sludge bed in mg/L; $\mu$ is the specific growth rate in per day; $K_d$ is the endogenous decay coefficient in per day; $Y$ is the cell yield coefficient in mg VSS/mg COD; $S_o$ is the influent substrate concentration in mg/L; and $S_e$ is the effluent substrate concentration in mg/L.

The ratio of total biomass in the reactor to biomass wasting rate is called SRT or referred as mean cell residence time ($\theta_c$). The $\theta_c$ is calculated using Eq. 4.3.

$$\theta_c = \frac{V_b \cdot X}{Q \cdot X_e} \tag{4.3}$$

(Metcalf & Eddy, 2003)

Eq. 4.4 shows the specific growth rate ($\mu$)

$$\mu = \frac{\mu_m \cdot S_e}{K_s + S_e} \tag{4.4}$$

(Wiesmann et al., 2007)

If it is presumed that biomass concentration of influent wastewater, $X_o$, is negligible and at steady state conditions, $\frac{dX}{dt} = 0$ and $\frac{dS}{dt} = 0$, then:

$$X = \frac{Q \cdot Y \cdot \theta_c \cdot (S_o - S_e)}{V_b \cdot (1 + K_d \cdot \theta_c)} \tag{4.5}$$

(Bhunia and Ghangrekar, 2008)

$$S_e = \frac{K_s \cdot (1 + K_d \cdot \theta_c)}{\theta_c \cdot (\mu_m - K_d) - 1} \tag{4.6}$$

(Bhunia and Ghangrekar, 2008)

Eqs. 4.5 and 4.6 are nonlinear in nature, hence it is indispensable to transform them to linearized forms. Two different linearized equations can be framed to obtain $Y$ and $K_d$ values, which are

$$\frac{Q \cdot (S_o - S_e)}{V_b \cdot X} = \frac{1}{Y} \cdot \frac{1}{\theta_c} + \frac{1}{Y} \cdot K_d \tag{4.7}$$

(Bhunia and Ghangrekar, 2008)

$$\frac{1}{\theta_c} = Y \cdot \frac{Q \cdot (S_o - S_e)}{V_b \cdot X \cdot \theta_c} - K_d \quad (4.8)$$

(Bhunia and Ghangrekar, 2008)

To obtain the estimates of $\mu_m$ and $K_s$, linear regression is applied on the linearized equation derived from substituting Eq. 4.6 into Eq. 4.2.

$$\frac{V_b \cdot S_e \cdot X}{Q \cdot (S_o - S_e)} = \frac{Y}{\mu_m} \cdot S_e + \frac{Y \cdot K_s}{\mu_m} \quad (4.9)$$

(Bhunia and Ghangrekar, 2008)

The other linear form of linearized equation reported in the literature for estimation of $\mu_m$ and $K_s$ are as follow

$$\frac{X \cdot V_b}{Q \cdot (S_o - S_e)} \cdot \frac{1}{Y} = \frac{K_s}{\mu_m} \cdot \frac{1}{S_e} + \frac{1}{\mu_m} \quad (4.10)$$

(Bhunia and Ghangrekar, 2008)

$$\frac{Q \cdot (S_o - S_e) \cdot Y}{V_b \cdot X} = \mu_m - K_s \frac{Q \cdot (S_o - S_e) \cdot Y}{X \cdot V_b \cdot S_e} \quad (4.11)$$

(Bhunia and Ghangrekar, 2008)

In order to determine the Monod kinetic model coefficients ($Y$, $K_d$, $\mu_m$ and $K_s$), the data (high strength influent) shown in Table 4.7 were plotted in Figure 4.46 and Figure 4.47. The values of $Y$ and $K_d$ were determined based on the linearized equation (Eq. 4.7). The values of $Y$ and $K_d$ were calculated from the intercept and slope of the linearized graphs (Figure 4.46). The values of $\mu_m$ and $K_s$ were determined based on the linearized equation (Eq. 4.9). The values of $\mu_m$ and $K_s$ were calculated from the intercept and slope of the linearized graphs and were shown in Figure 4.47. Table 4.8 shows the Monod kinetic model coefficients obtain in this study for the reactors. High $R^2$ values ($R^2$>0.9) were obtained for $Y$ and $K_d$ determinations for all reactors and $\mu_m$ and $K_s$ determinations for UASB reactors. However, the $R^2$ values were lower for $\mu_m$ and $K_s$ determinations (0.7023 and 0.6797) for HUASB reactors.

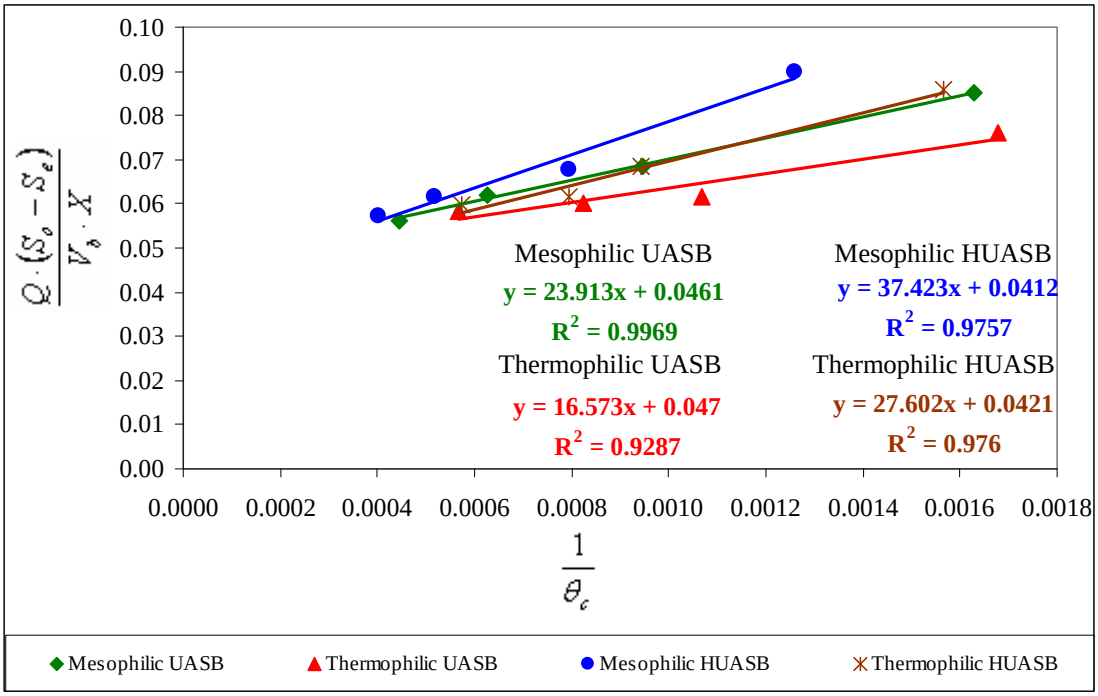


Figure 4.46 Determination of Monod kinetic model coefficients, $Y$ and $K_d$ values

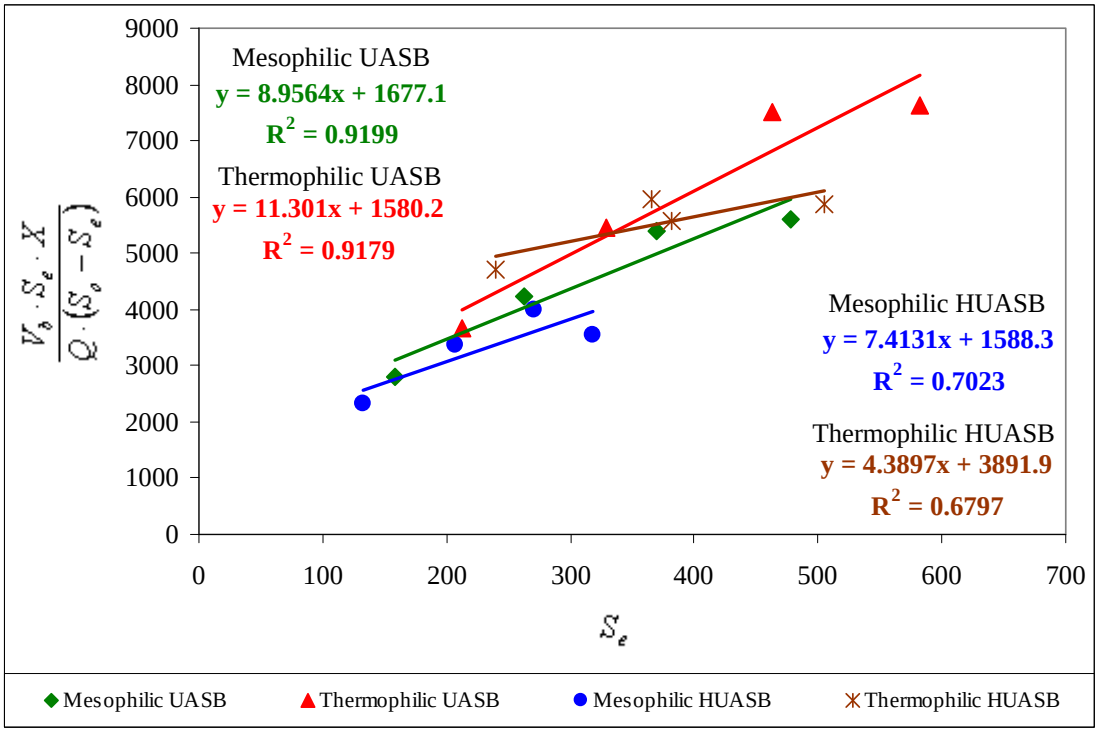


Figure 4.47 Determination of Monod kinetic model coefficients, $\mu_m$ and $K_s$ values

Table 4.8 Monod kinetic model coefficients

| Reactor | $Y$ | $K_d$ (per day) | $R^2$ | $\mu_m$ (per day) | $K_s$ (mg/L) | $R^2$ |
|---|---|---|---|---|---|---|
| Mesophilic UASB | 0.042 | 0.00193 | 0.9969 | 0.00467 | 187.3 | 0.9199 |
| Thermophilic UASB | 0.060 | 0.00284 | 0.9287 | 0.00534 | 139.8 | 0.9179 |
| Mesophilic HUASB | 0.027 | 0.00110 | 0.9757 | 0.00371 | 220.6 | 0.7023 |
| Thermophilic HUASB | 0.036 | 0.00153 | 0.9760 | 0.00825 | 886.6 | 0.6797 |

($Y$ in mg VSS/mg COD)

### 4.4.2 Application of Modified Stover-Kincannon Kinetic Model

Stover-Kincannon is one of the most widely used mathematical model for determining the kinetic constant in biofilm reactors. The Stover-Kincannon model considers the organic substance removal rate as a function of organic loading rate at steady state as in Eq. 4.12

$$\frac{dS}{dt} = \frac{Q}{V} \cdot \left(S_o - S_e\right) \tag{4.12}$$

(Buyukkamaci and Filibeli, 2002; Kapdan, 2005)

Equations of the modified Stover-Kincannon model are follows:

$$\frac{dS}{dt} = \frac{U_{\max} \cdot \left(\frac{Q \cdot S_i}{V}\right)}{K_B + \left(\frac{Q \cdot S_o}{V}\right)} \tag{4.13}$$

(Buyukkamaci and Filibeli, 2002; Kapdan, 2005)

where, $K_B$ saturation value constant (modified Stover-Kincannon) in g/L·day; $U_{max}$ maximum substrate removal rate (modified Stover-Kincannon), in g/L·day

Eq. 4.14 obtained from linearization of Eqs. 4.12 and 4.13 as follows:

$$\frac{V}{Q \cdot \left(S_o - S_e\right)} = \frac{K_B}{U_{\max}} \cdot \frac{V}{Q \cdot S_o} + \frac{1}{U_{\max}} \tag{4.14}$$

(Buyukkamaci and Filibeli, 2002; Kapdan, 2005)

In order to determine the modified Stover-Kincannon kinetic model coefficients ($K_B$ and $U_{max}$), the data (high strength influent) shown in Table 4.7 were plotted in Figure 4.48. The values of $K_B$ and $U_{max}$ were determined based on the linearized equation (Eq. 4.14). The values of $K_B$ and $U_{max}$ were calculated from the intercept and slope of the linearized graphs. Table 4.9 shows the modified Stover-Kincannon kinetic model coefficients obtain in this study for the reactors. High $R^2$ values ($R^2$>0.9) were obtained for $K_B$ and $U_{max}$ determinations for all reactors.

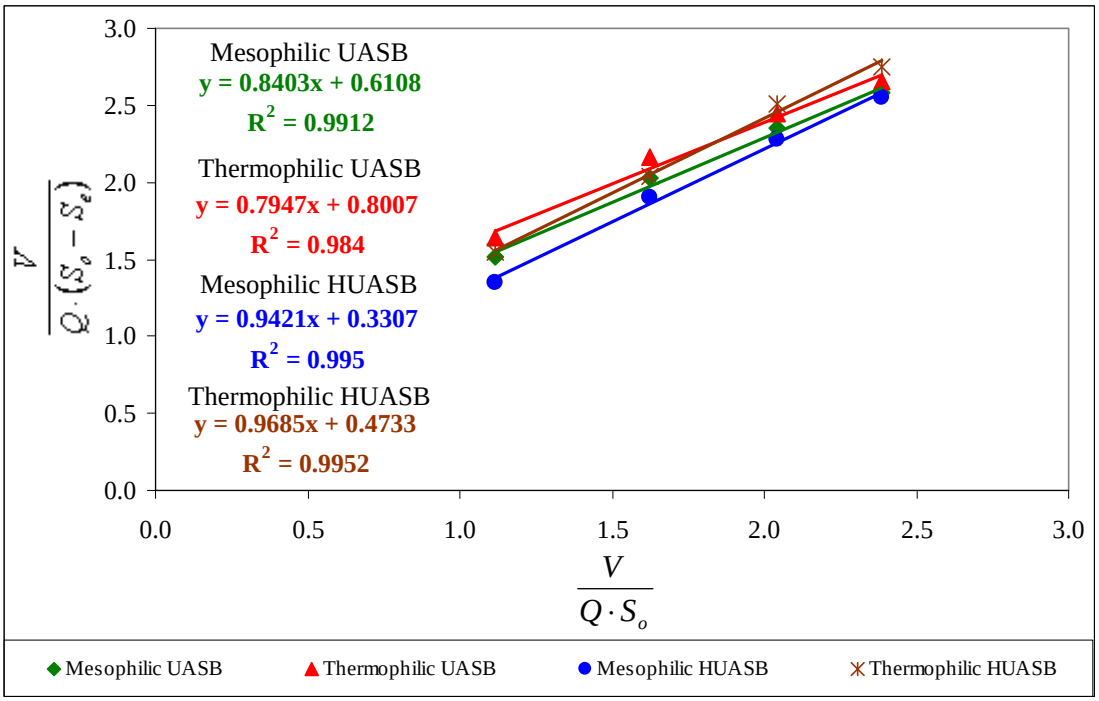


Figure 4.48 Determination of modified Stover-Kincannon kinetic model coefficients, $K_B$ and $U_{max}$ values

Table 4.9 Modified Stover-Kincannon kinetic model coefficients

| Reactor | $K_B$ (g/L·day) | $U_{max}$ (g/L·day) | $R^2$ |
|---|---|---|---|
| Mesophilic UASB | 1.376 | 1.637 | 0.9912 |
| Thermophilic UASB | 0.993 | 1.2489 | 0.984 |
| Mesophilic HUASB | 2.849 | 3.024 | 0.995 |
| Thermophilic HUASB | 2.046 | 2.113 | 0.9952 |

### 4.4.3 Application Grau Second-order Multi-component Substrate Removal Kinetic Model

The general equation of a second order kinetic model used for predicting the behaviour of reactors for estimating kinetic coefficients is given in Eq. 4.15.

$$\frac{dS}{dt} = K_{s2} \cdot X \cdot \left( \frac{Se}{S_o} \right)^2 \tag{4.15}$$

(Metcalf & Eddy, 2003)

If Eq. 4.15 is integrated ($S = S_o$ to $S_e$; and $t = 0$ to $\theta_H$), the linearized Eq. 4.16 will be obtained:

$$\frac{S_o \cdot \theta_H}{S_o - S_e} = \theta_H + \frac{S_o}{K_{s2} \cdot X} \tag{4.16}$$

(Bhunia and Ghangrekar, 2008)

If the second part of the right hand side in Eq. 4.16 is a constant "*a*", Eq. 4.17 will be obtained

$$\frac{S_o \cdot \theta_H}{S_o - S_e} = a + b \cdot \theta_H \tag{4.17}$$

(Bhunia and Ghangrekar, 2008)

where, the substrate removal kinetic constant $a = \frac{S_o}{K_{s2} \cdot X}$ and the coefficient b in Eq. 4.17 is close to one and generally reflects the impracticality of attaining a zero value of COD. The substrate removal efficiency is expressed as $\frac{S_o - S_e}{S_o}$ and is symbolized as *E*. Therefore, the final equation of Grau kinetic model can be written as

$$\frac{\theta_H}{E} = a + b \cdot \theta_H \tag{4.18}$$

(Bhunia and Ghangrekar, 2008)

In order to determine the kinetic coefficients (*a, b and* $k_{s2}$) applying Eq. 4.18, a graph can be plotted with $\theta_H$ versus $\frac{\theta_H}{E}$. The values *a* and *b* are calculated from the intercept and slope of the straight line.

In order to determine the kinetic coefficients (*a, b*), the data set shown Table 4.7 was plotted in Figure 4.49. The values of *a* and *b* were calculated from the intercept and slope of the linearized graph. Table 4.10 shows the values of kinetic parameter obtain in this study for the reactors. High $R^2$ values ($R^2$>0.9) were obtained for *a* and *b* determinations for all reactors.

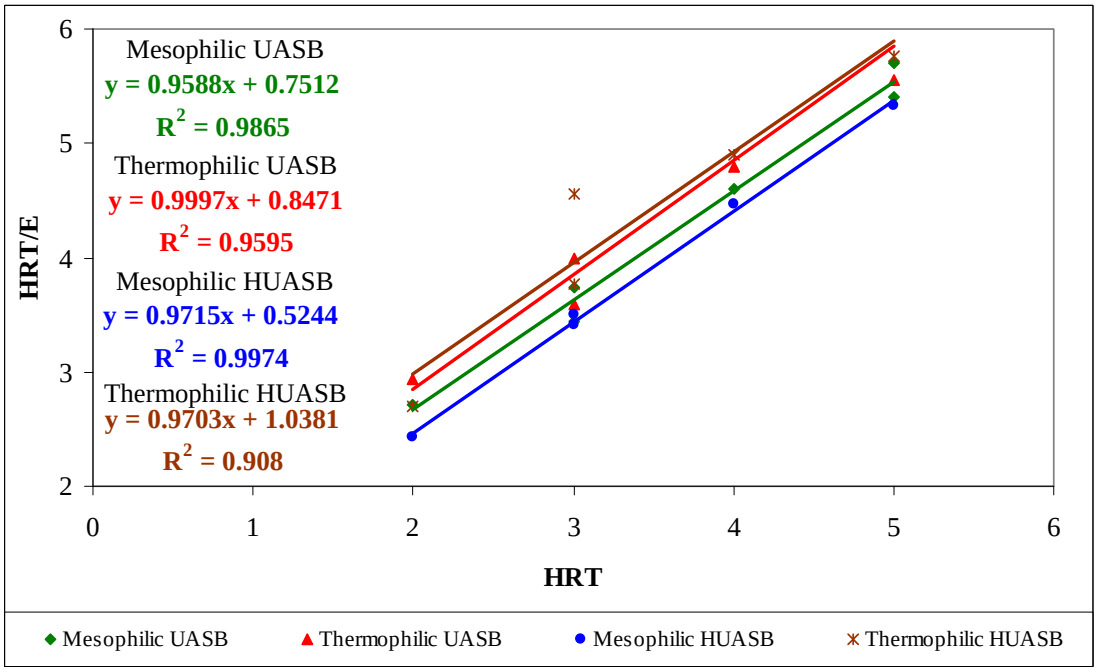


Figure 4.49 Determination of Grau second-order kinetic model coefficients

Table 4.10 Grau second-order kinetic model coefficients

| Reactor | *a* (per day) | *b* | $R^2$ |
|---|---|---|---|
| Mesophilic UASB | 0.7512 | 0.9588 | 0.9865 |
| Thermophilic UASB | 0.8417 | 0.9997 | 0.9595 |
| Mesophilic HUASB | 0.5255 | 0.9715 | 0.9974 |
| Thermophilic HUASB | 1.0381 | 0.9703 | 0.908 |

### 4.4.4 Evaluation of the Kinetic Models

Table 4.11, Table 4.12 and Table 4.13 show the comparisons of Monod, modified Stover-Kincannon and Grau second-order kinetic model coefficients, respectively. The Monod model is widely used for UASB reactors and other industrial biological reactors. The Monod kinetic model has been applied to anaerobic treatment of various type of wastewater, including synthetic wastewater (Bhunia and Ghangrekar, 2008), simulated textile wastewater (Isik and Sponza, 2005), municipal wastewater (Singh and Viraraghavan, 2002) and POME wastewater (Zinatizadeh et al., 2006).

The modified Stover-Kincannon kinetic model has been applied to mesophilic and thermophilic AF for synthetic starch wastewater (Ahn and Forster, 2000), mesophilic HUASB for synthetic molasses wastewater (Buyukkamaci and Filibeli, 2002), mesophilic UASB for textile wastewater (Isik and Sponza, 2005) and mesophilic UAFB for formaldehyde and textile wastewater (Priya et al., 2009; Sandhya and Swaminathan, 2006). The maximum COD removal rate ($U_{max}$) and saturation value constant ($K_B$) in this study were lower than modified Stover-Kincannon kinetic model coefficients that were obtained by Ahn and Foster (2000), Buyukkamaci and Filibeli (2002), Isik and Sponza (2005) and Sandhya and Swaminathan (2006). However, the values of $U_{max}$ and $K_B$ in this study were similar with kinetic model coefficients that were obtained by Priya et al. (2009).

The Grau second-order kinetic model has been applied successfully to anaerobic treatment of various type of wastewater, including synthetic wastewater (Bhunia and Ghangrekar, 2008), poultry slaughterhouse wastewater (Debik and Coskun, 2009), simulated textile wastewater (Isik and Sponza, 2005), synthetic *para*-nitrophenol wastewater (Kuscu and Sponza, 2009) and simulated synthetic coal (Ramakrishnan and Gupta, 2008). The values of *a* in this study were similar with the values of *a* that were obtained by Bhunia and Ghangrekar (2008) and Isik and Sponza (2005).

Table 4.11 Comparison of Monod kinetic model coefficients

| Wastewater | Type of reactors | Influent COD | HRT | Kinetic parameters | | | | References |
|---|---|---|---|---|---|---|---|---|
| Monod | | | | $Y$ | $K_d$ | $\mu_m$ | $K_s$ | |
| Pharmaceutical | Mesophilic UASB | 1820-2127 mg/L | 2-5 d | 0.042 | 0.00193 | 0.00467 | 187.3 | This study |
| Pharmaceutical | Thermophilic UASB | 1820-2127 mg/L | 2-5 d | 0.060 | 0.00284 | 0.00534 | 139.8 | This study |
| Pharmaceutical | Mesophilic HUASB | 1820-2127 mg/L | 2-5 d | 0.027 | 0.00110 | 0.00371 | 220.6 | This study |
| Pharmaceutical | Thermophilic HUASB | 1820-2127 mg/L | 2-5 d | 0.036 | 0.00153 | 0.00825 | 886.6 | This study |
| Synthetic | UASB | 300-2000 | 4-8 h | 0.083 | 0.006 | 0.058 | 226.1 | (Bhunia and Ghangrekar, 2008) |
| Simulated textile | Mesophilic UASB | 4214 mg/L | 6-100 h | 0.125 | 0.0065 | 0.105 | >4000 | (Isik and Sponza, 2005) |
| Municipal | Mesophilic UASB | 250-550 mg/L | 3-48 h | 0.422 | 0.0033 | 0.16 | 601 | (Singh and Viraraghavan, 2002) |
| POME | Mesophilic UASFF | 5260-34725 mg/L | 1-6 d | 0.174 | N/S | 0.287 | 982 | (Zinatizadeh et al., 2006) |

($Y$ in mg VSS/mg COD; $K_d$ in per day; $\mu_m$ in per day; $K_d$ in per day)

Table 4.12 Comparison of modified Stover-Kincannon kinetic model coefficients

| Wastewater | Type of reactors | Influent COD | HRT | Kinetic parameters | | References |
|---|---|---|---|---|---|---|
| Modified Stover-Kincannon | | | | $U_{max}$ (g/L·d) | $K_B$ (g/L·d) | |
| Pharmaceutical | Mesophilic UASB | 1820-2127 mg/L | 2-5 d | 1.637 | 1.376 | This study |
| Pharmaceutical | Thermophilic UASB | 1820-2127 mg/L | 2-5 d | 1.2489 | 0.993 | This study |
| Pharmaceutical | Mesophilic HUASB | 1820-2127 mg/L | 2-5 d | 3.024 | 2.849 | This study |
| Pharmaceutical | Thermophilic HUASB | 1820-2127 mg/L | 2-5 d | 2.113 | 2.046 | This study |
| Synthetic starch | Mesophilic AF | 2000-4000 mg/L | 24 h | 49.8 | 50.6 | (Ahn and Forster, 2000) |
| Synthetic starch | Thermophilic AF | 2000-4000 mg/L | 24 h | 66.7 | 70.2 | (Ahn and Forster, 2000) |
| Synthetic molasses | Mesophilic HUASB | 1-10 g COD/L·d | 0.5-2 d | 83.3 | 186.23 | (Buyukkamaci and Filibeli, 2002) |
| Poultry slaughterhouse | Static Anaerobic Sludge Bed Reactor | 6880±1400 mg/L | 36-60 | 121.71 | 130.28 | (Debik and Coskun, 2009) |
| Poultry slaughterhouse | Static Granular Bed Reactor | 6880±1400 mg/L | 36-60 | 164.48 | 177.21 | (Debik and Coskun, 2009) |
| Simulated textile | Mesophilic UASB | 4214 mg/L | 6-100 h | 8.211 | 7.501 | (Isik and Sponza, 2005) |
| Synthetic dye | Upflow anaerobic packed bed reactor | 1-8 g/L·d | N/S | 12.9 | 37.9 | (Kapdan, 2005) |
| Industrial pig farming | Anaerobic bioreactor | 3150 mg/L | 0.6-10 d | 80.9 | 91.582 | (Kosinska and Miskiewicz, 2009) |
| Synthetic *para*-nitrophenol | AMBR | 3000 mg/L | 1-10.38 d | 29.49 | 31.55 | (Kuscu and Sponza, 2009) |
| Formaldehyde | Mesophilic UAFB | 10976-11840 mg/L | 6-24 h | 3.4 | 4.6 | (Priya et al., 2009) |
| Textile | Mesophilic UAFB | 1835-3828 mg/L | 9.9-23.76 h | 31.69 | 45.37 | (Sandhya and Swaminathan, 2006) |

Table 4.13 Comparison of Grau second-order kinetic model coefficients

| Wastewater | Type of reactors | Influent COD | HRT | Kinetic parameters | | References |
|---|---|---|---|---|---|---|
| Grau second-order | | | | *a* (per d) | *b* | |
| Pharmaceutical | Mesophilic UASB | 1820-2127 mg/L | 2-5 d | 0.7512 | 0.9588 | This study |
| Pharmaceutical | Thermophilic UASB | 1820-2127 mg/L | 2-5 d | 0.8417 | 0.9997 | This study |
| Pharmaceutical | Mesophilic HUASB | 1820-2127 mg/L | 2-5 d | 0.5255 | 0.9715 | This study |
| Pharmaceutical | Thermophilic HUASB | 1820-2127 mg/L | 2-5 d | 1.0381 | 0.9703 | This study |
| Synthetic | UASB | 300-2000 | 4-8 h | 0.558 | 1.043 | (Bhunia and Ghangrekar, 2008) |
| Poultry slaughterhouse | Static Anaerobic Sludge Bed Reactor | 6880±1400 mg/L | 36-60 h | 0.098 | 1.100 | (Debik and Coskun, 2009) |
| Poultry slaughterhouse | Static Granular Bed Reactor | 6880±1400 mg/L | 36-60 h | 0.173 | 1.155 | (Debik and Coskun, 2009) |
| Simulated textile | Mesophilic UASB | 4214 mg/L | 6-100 h | 0.562 | 1.095 | (Isik and Sponza, 2005) |
| Synthetic *para*-nitrophenol | AMBR | 3000 mg/L | 1-10.38 d | 0.0958 | 1.071 | (Kuscu and Sponza, 2009) |
| Simulated synthetic coal | Mesophilic HUASB | 2240 | 18-36 h | 0.0783 | 0.9645 | (Ramakrishnan and Gupta, 2008) |

Bhunia and Ghangrekar (2008) reported that the Grau second-order kinetic was found as the best class of fit for wide range of data set in UASB reactor. The value of *a* and *b* were 0.558 and 1.043, respectively, in UASB reactor that was treating synthetic wastewater in the range of 300-4000 mg COD/L. Isik and Sponza (2005) reported that Grau second-order and modified Stover-Kincannon kinetic models were found to be more suitable than Monod, Contois and first-order kinetic models in mesophilic UASB reactor.

Figure 4.50 to Figure 4.53 show the comparisons of the measured and predicted COD concentration in UASB and HUASB reactors. In mesophilic and thermophilic UASB reactors, high $R^2$ values ($R^2$>0.9) were obtained in the comparisons of measured and predicted effluent COD for modified Stover-Kincannon and Grau second-order kinetic models. They indicated high correlations between the measured and predicted effluent COD data and the linear regression lines. However, the $R^2$ values were lower for Monod kinetic model in mesophilic and thermophilic UASB reactors (0.8165 and 0.8065). In mesophilic UASB reactor, the measured and predicted effluent COD values were similar based on linear regression equations for modified Stover-Kincannon $(y = 0.9923x + 3.4313)$ and Grau second-order $(y = 0.9334x + 3.6452)$ kinetic models (Figure 4.50). However, the predicted effluent COD value was higher than the measured effluent COD value in Monod kinetic model $(y = 1.2144x - 55.085)$.

In thermophilic UASB reactor, the measured and predicted effluent COD value were similar based on linear regression equation only for modified Stover-Kincannon $(y = 0.9923x + 3.4313)$ kinetic model (Figure 4.51). The predicted effluent COD value was higher than the measured effluent value in Monod kinetic model $(y = 1.2144x - 55.085)$ and the predicted effluent COD value was lower than the measured effluent COD value in Grau second-order kinetic model $(y = 0.8605x + 45.11)$

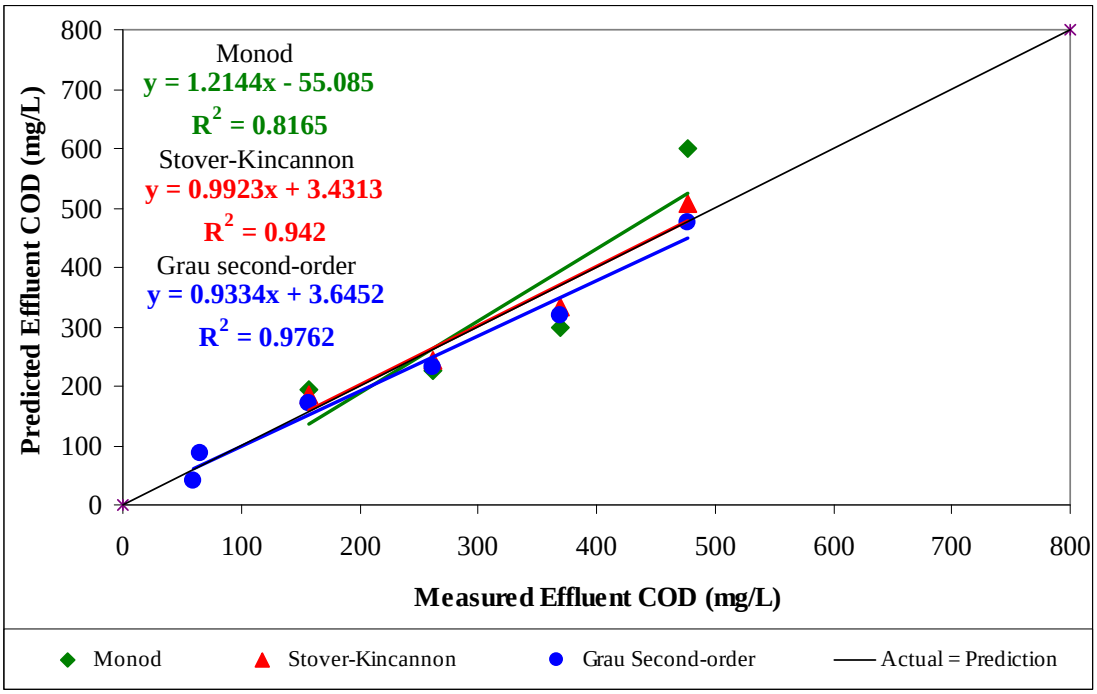


Figure 4.50 Comparison of the measured and predicted effluent COD in mesophilic UASB reactor

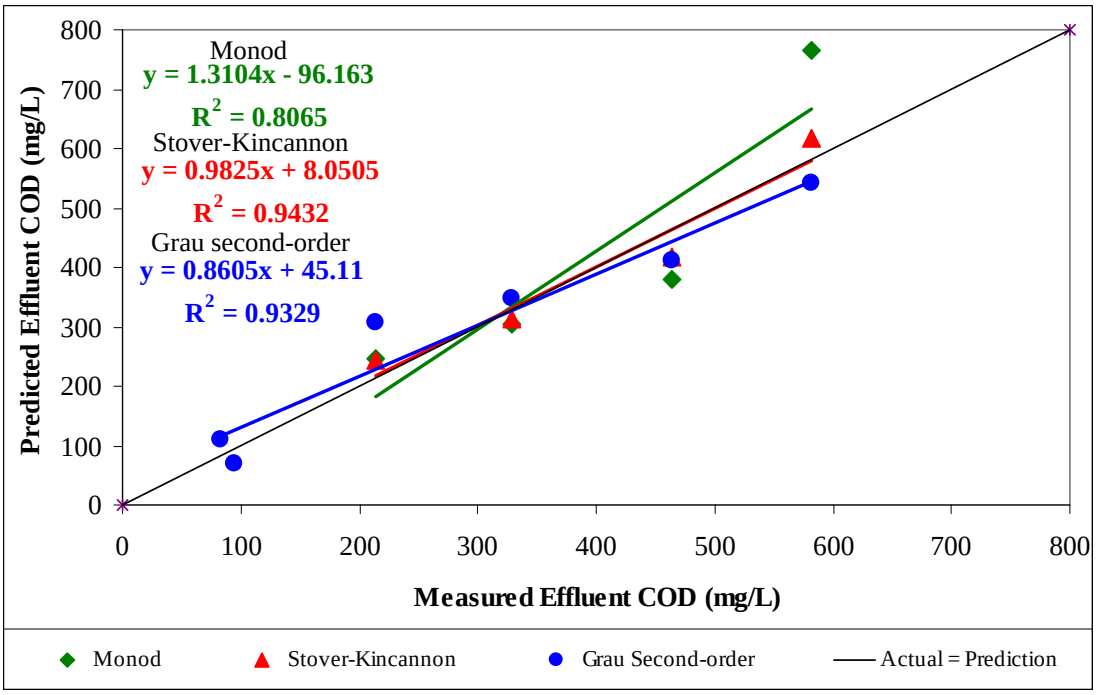


Figure 4.51 Comparison of the measured and predicted effluent COD in thermophilic UASB reactor

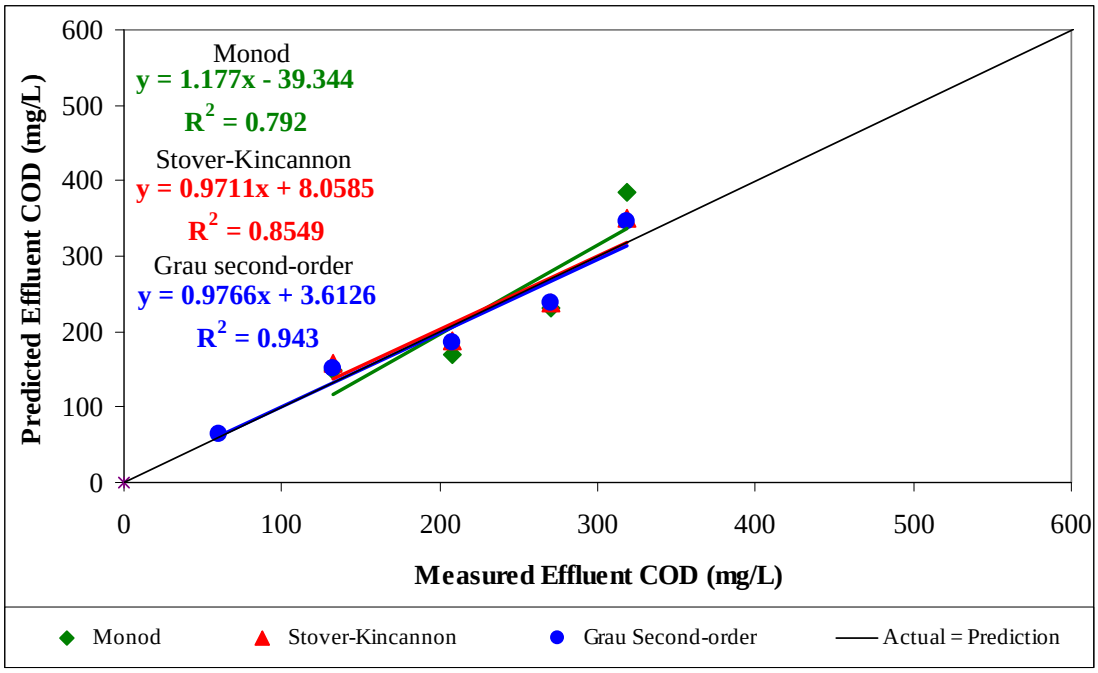


Figure 4.52 Comparison of the measured and predicted effluent COD in mesophilic HUASB reactor

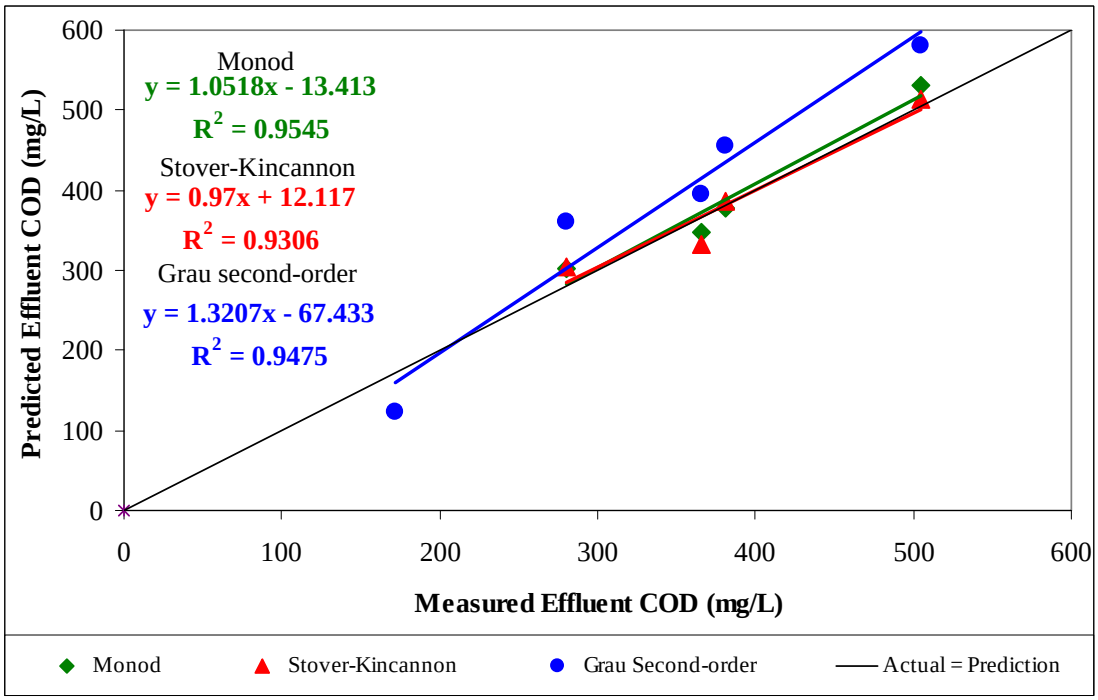


Figure 4.53 Comparison of the measured and predicted effluent COD in thermophilic HUASB reactor

In mesophilic HUASB reactor, high $R^2$ value ($R^2$>0.9) was obtained in the comparison of measured and predicted effluent COD for Grau second-order kinetic model. It indicated high correlation between the measured and predicted effluent COD data and the linear regression line. However, the $R^2$ values were lower for Monod and modified Stover-Kincannon kinetic model (0.792 and 0.8549). The measured and predicted effluent COD values were similar based on linear regression equations for modified Stover-Kincannon $(y = 0.9711x + 8.0585)$ and Grau second-order $(y = 0.9766x + 3.6126)$ kinetic models (Figure 4.52). However, the predicted effluent COD value was higher than the measured effluent COD value in Monod kinetic model $(y = 1.177x - 39.344)$.

In thermophilic HUASB reactor, high $R^2$ values ($R^2$>0.9) were obtained in the comparisons of measured and predicted effluent COD for all kinetic models. They indicated high correlations between the measured and predicted effluent COD data and the linear regression lines. The measured and predicted effluent COD values were similar based on linear regression equations for Monod $(y = 1.0518x - 13.413)$ and modified Stover-Kincannon $(y = 0.97x + 12.117)$ kinetic models (Figure 4.53). The predicted effluent COD value was higher than the measured effluent value in Grau second-order kinetic model $(y = 1.3207x - 67.433)$.

# CHAPTER 5
# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The biological wastewater treatment study was performed to treat non-penicillin pharmaceutical wastewater. The study was conducted in two phases. The Phase I study observed the performance of semi-anaerobic and aerobic reactors in treating non-penicillin pharmaceutical wastewater. The Phase II was carried out on anaerobic treatment processes. Based on the performance observation of semi-anaerobic and aerobic reactors, the following conclusions can be drawn:

a. Train 1 (SABR-ASP reactor) achieves higher COD removal in treating the high strength wastewater (COD 1953 mg/L); however, Train 2 (ASP reactor) achieves higher COD removal in treating the low strength wastewater (COD 635 mg/L).
b. The aerobic biomass from a sewage treatment plant can be successfully used as seed biomass in aerobic and semi-anaerobic reactors in treating non-penicillin pharmaceutical wastewater.

The objective of this study was to evaluate the performance of mesophilic and thermophilic UASB and HUASB reactors in treating non-penicillin pharmaceutical wastewater. The reactors were seeded with sludge from an aerobic domestic sewage treatment plant. The pharmaceutical wastewater was very fluctuative in COD and $BOD_5$ concentrations. The reactors were fed with low strength influent (COD 458-526 mg/L) and high strength influent (COD 1770-2217 mg/L). Based on the performance evaluation of mesophilic and thermophilic UASB and HUASB reactors, the following conclusions can be drawn:

a. The HUASB reactors are significantly more efficient in COD removal than the UASB reactors. The UASB and HUASB reactors showed higher COD removals in treating the high strength wastewater.

b. The concentrations of $NH_3$-N and total phosphorous increase, whereas the concentration of $NO_3$-N remains constant and concentration of TKN slightly reduces.

This study evaluated the effect of HRT and temperature on the performance of UASB and HUASB reactors. The reactors were operated under mesophilic (35±2°C) and thermophilic (55±2°C) temperatures and HRTs of five, four, three and two days. Based on the evaluation of the operation condition effect in mesophilic and thermophilic UASB and HUASB reactors, the following conclusions can be drawn:

a. The reactor performance is significantly affected by type of reactors, HRT and temperature.
b. Mesophilic UASB and HUASB reactors achieve higher COD and $BOD_5$ removals than both thermophilic reactors in treating pharmaceutical wastewater.
c. The COD and $BOD_5$ removals decrease when the HRT was decreased.
d. The highest average COD and $BOD_5$ removals are achieved by the mesophilic HUASB reactor treating high strength pharmaceutical wastewater at HRT of five days (average OLR 0.43 g COD/L·day); average COD removal is 90%, average effluent COD is 133 mg/L, average $BOD_5$ removal is 97% and average effluent $BOD_5$ is 51 mg/L.
e. The lowest average COD and $BOD_5$ removals are achieved by the thermophilic UASB reactor at HRT of two days. The average COD and $BOD_5$ removals are 68% and 76%, respectively, whereas the average COD and $BOD_5$ concentrations are 582 mg/L and 299 mg/L, respectively.

Three kinetics models i.e. Monod, modified Stover-Kincannon and Grau second-order were applied in this study to determine the kinetics of pharmaceutical wastewater treatment using UASB and HUASB reactors. The results of kinetic model analysis indicate:

a. Grau second-order fits well for estimates of kinetic coefficients in all reactors. High $R^2$ values ($R^2$>0.9) were obtained for *a* and *b* determinations for all reactors.

b. Among the three kinetic models, Grau second order model is observed to be the preeminent model for predicting the performance of UASB and HUASB reactors. In mesophilic and thermophilic UASB reactors, the values of *a* are 0.8822 and 0.8471 per day and the values of *b* are and 0.9111 and 0.9997, respectively. In mesophilic and thermophilic HUASB reactors, the values of *a* are 0.5244 and 0.8767 per day and the values of *b* are and 0.9715 and 1.029, respectively.

c. In Monod kinetic model, high $R^2$ values ($R^2$>0.9) are obtained for $Y$ and $K_d$ determinations for all reactors and $\mu_m$ and $K_s$ determinations for UASB reactors. However, the $R^2$ values are lower for $\mu_m$ and $K_s$ determinations (0.7023 and 0.6797) for HUASB reactors. In mesophilic UASB reactor, the values of $Y$ and $K_d$ are 0.042 mg VSS/mg COD and 0.00193 per day, whereas in thermophilic UASB reactor, the values of $Y$ and $K_d$ are 0.060 mg VSS/mg COD and 0.00284 per day, respectively. The values of $\mu_m$ and $K_s$ are 0.00467 per day and 187.3 mg/L in mesophilic UASB reactor, while in thermophilic UASB reactor, the values of $\mu_m$ and $K_s$ are 0.00534 per day and 139.8 mg/L, respectively. In mesophilic HUASB reactor, the values of $Y$ and $K_d$ are 0.027 mg VSS/mg COD and 0.00110 per day, whereas in thermophilic HUASB reactor, the values of $Y$ and $K_d$ are 0.036 mg VSS/mg COD and 0.00153 per day, respectively. The values of $\mu_m$ and $K_s$ are 0.00371 per day and 220.6 mg/L in mesophilic HUASB reactor, whereas in thermophilic HUASB reactor, the values of $\mu_m$ and $K_s$ are 0.00825 per day and 886.6 mg/L, respectively.

## 5.2 Recommendations

This study has shown that both UASB and HUASB reactors have potential to be used as treatment alternatives for non-penicillin pharmaceutical wastewater. However, the UASB and HUASB reactors require post treatment in treating high strength pharmaceutical wastewater. Moreover, nutrient treatment is required because the nutrient removals were negligible during this study. Combined treatment for organics and nutrients removal, using anaerobic process and other biological process can be

used as an alternative for non-penicillin pharmaceutical wastewater treatment. Response of UASB and HUASB reactors to shock loads from non-penicillin pharmaceutical wastewater may be studied. Further study is required to study the effect of acclimatization period and method on the anaerobic reactor performance.

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## APPENDIX A
## PARAMETER ANALYSIS

COD data for the UASB and HUASB reactors

Table A.1 Influent and effluent COD concentrations, OLR, and COD removal data in the mesophilic and thermophilic UASB reactors

| Date | Days | Influent COD (mg/L) | | | | OLR | Effluent COD M-UASB (mg/L) | | | | Rem. | Effluent COD T-UASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | (g COD/L/.d) | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| Low strength influent; HRT of five days | | | | | | | | | | | | | | | | |
| 30-Nov-07 | 1 | 487 | 504 | 499 | 497 | 0.10 | 64 | 64 | 63 | 64 | 87.18 | 291 | 296 | 295 | 294 | 40.81 |
| 02-Dec-07 | 3 | 491 | 493 | 496 | 493 | 0.10 | 67 | 72 | 68 | 69 | 86.01 | 178 | 179 | 187 | 181 | 63.24 |
| 04-Dec-07 | 5 | 513 | 483 | 494 | 497 | 0.10 | 73 | 73 | 67 | 71 | 85.70 | 168 | 160 | 156 | 161 | 67.52 |
| 06-Dec-07 | 7 | 500 | 501 | 495 | 499 | 0.10 | 69 | 62 | 63 | 65 | 87.03 | 124 | 117 | 119 | 120 | 75.94 |
| 08-Dec-07 | 9 | 471 | 468 | 469 | 469 | 0.09 | 47 | 48 | 48 | 48 | 89.84 | 84 | 76 | 80 | 80 | 82.95 |
| 10-Dec-07 | 11 | 462 | 458 | 454 | 458 | 0.09 | 43 | 43 | 43 | 43 | 90.61 | 77 | 78 | 79 | 78 | 82.97 |
| 12-Dec-07 | 13 | 500 | 496 | 502 | 499 | 0.10 | 54 | 60 | 66 | 60 | 87.98 | 108 | 97 | 99 | 101 | 79.71 |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | | |
| 16-Dec-07 | 17 | 504 | 515 | 518 | 512 | 0.17 | 82 | 91 | 87 | 87 | 83.08 | 141 | 134 | 131 | 135 | 73.58 |
| 18-Dec-07 | 19 | 503 | 502 | 513 | 506 | 0.17 | 63 | 56 | 65 | 61 | 87.88 | 116 | 112 | 103 | 110 | 78.19 |
| 20-Dec-07 | 21 | 499 | 491 | 478 | 489 | 0.16 | 64 | 52 | 59 | 58 | 88.08 | 113 | 120 | 115 | 116 | 76.29 |
| 22-Dec-07 | 23 | 510 | 495 | 489 | 498 | 0.17 | 59 | 56 | 62 | 59 | 88.15 | 111 | 108 | 110 | 110 | 77.98 |
| 24-Dec-07 | 25 | 494 | 493 | 504 | 497 | 0.17 | 71 | 69 | 72 | 71 | 85.78 | 129 | 126 | 132 | 129 | 74.04 |
| 26-Dec-07 | 27 | 508 | 498 | 519 | 508 | 0.17 | 75 | 80 | 79 | 78 | 84.66 | 146 | 136 | 139 | 140 | 72.39 |
| 28-Dec-07 | 29 | 473 | 493 | 498 | 488 | 0.16 | 86 | 85 | 81 | 84 | 82.79 | 139 | 137 | 129 | 135 | 72.34 |
| 01-Jan-08 | 33 | 490 | 483 | 482 | 485 | 0.16 | 108 | 94 | 94 | 99 | 79.66 | 146 | 139 | 140 | 142 | 70.79 |
| 03-Jan-08 | 35 | 504 | 503 | 513 | 507 | 0.17 | 88 | 89 | 85 | 87 | 82.76 | 123 | 131 | 127 | 127 | 74.93 |
| 07-Jan-08 | 39 | 526 | 518 | 518 | 521 | 0.17 | 89 | 87 | 77 | 84 | 83.80 | 112 | 115 | 111 | 113 | 78.36 |
| 09-Jan-08 | 41 | 515 | 517 | 515 | 516 | 0.17 | 76 | 76 | 67 | 73 | 85.84 | 95 | 99 | 98 | 97 | 81.12 |
| 11-Jan-08 | 43 | 493 | 499 | 493 | 495 | 0.17 | 64 | 65 | 67 | 65 | 86.80 | 98 | 99 | 92 | 96 | 80.54 |
| 13-Jan-08 | 45 | 500 | 512 | 498 | 503 | 0.17 | 67 | 67 | 65 | 66 | 86.82 | 111 | 115 | 117 | 114 | 77.28 |
| 15-Jan-08 | 47 | 478 | 488 | 483 | 483 | 0.16 | 68 | 67 | 68 | 68 | 85.99 | 91 | 99 | 98 | 96 | 80.12 |

Table A.1 (Continued)

| Date | Days | Influent COD (mg/L) | | | | OLR | Effluent COD M-UASB (mg/L) | | | | Rem. | Effluent COD T-UASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | (g COD/L/.d) | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| Low strength influent; HRT of three days (continued) | | | | | | | | | | | | | | | | |
| 17-Jan-08 | 49 | 487 | 488 | 482 | 486 | 0.16 | 52 | 55 | 57 | 55 | 88.74 | 95 | 89 | 93 | 92 | 80.99 |
| 21-Jan-08 | 53 | 526 | 520 | 532 | 526 | 0.18 | 51 | 46 | 47 | 48 | 90.87 | 75 | 67 | 66 | 69 | 86.82 |
| 23-Jan-08 | 55 | 511 | 498 | 493 | 501 | 0.17 | 65 | 54 | 55 | 58 | 88.42 | 73 | 72 | 68 | 71 | 85.82 |
| 25-Jan-08 | 57 | 503 | 529 | 518 | 517 | 0.17 | 59 | 61 | 66 | 62 | 88.00 | 71 | 69 | 79 | 73 | 85.87 |
| 27-Jan-08 | 59 | 504 | 514 | 519 | 512 | 0.17 | 63 | 65 | 63 | 64 | 87.57 | 70 | 86 | 73 | 76 | 85.10 |
| 29-Jan-08 | 61 | 520 | 514 | 512 | 515 | 0.17 | 61 | 68 | 62 | 64 | 87.65 | 73 | 75 | 81 | 76 | 85.19 |
| 31-Jan-08 | 63 | 520 | 524 | 514 | 519 | 0.17 | 43 | 47 | 53 | 48 | 90.82 | 79 | 76 | 81 | 79 | 84.85 |
| 02-Feb-08 | 65 | 504 | 531 | 501 | 512 | 0.17 | 54 | 47 | 49 | 50 | 90.23 | 75 | 65 | 73 | 71 | 86.13 |
| 04-Feb-08 | 67 | 521 | 502 | 505 | 509 | 0.17 | 45 | 52 | 54 | 50 | 90.12 | 79 | 85 | 82 | 82 | 83.90 |
| 06-Feb-08 | 69 | 506 | 507 | 516 | 510 | 0.17 | 49 | 51 | 54 | 51 | 89.93 | 66 | 72 | 82 | 73 | 85.61 |
| 10-Feb-08 | 73 | 505 | 512 | 500 | 506 | 0.17 | 51 | 51 | 54 | 52 | 89.72 | 65 | 68 | 66 | 66 | 86.88 |
| 12-Feb-08 | 75 | 499 | 508 | 501 | 503 | 0.17 | 52 | 48 | 61 | 54 | 89.32 | 66 | 71 | 75 | 71 | 85.94 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | | |
| 14-Feb-08 | 77 | 2110 | 2160 | 2150 | 2140 | 0.43 | 75 | 77 | 76 | 76 | 96.45 | 106 | 124 | 115 | 115 | 94.63 |
| 16-Feb-08 | 79 | 2200 | 2240 | 2210 | 2217 | 0.44 | 94 | 95 | 97 | 95 | 95.70 | 169 | 174 | 165 | 169 | 92.36 |
| 18-Feb-08 | 81 | 2200 | 2140 | 2150 | 2163 | 0.43 | 120 | 124 | 123 | 122 | 94.35 | 144 | 155 | 150 | 150 | 93.08 |
| 20-Feb-08 | 83 | 2150 | 2130 | 2130 | 2137 | 0.43 | 133 | 131 | 132 | 132 | 93.82 | 199 | 201 | 201 | 200 | 90.62 |
| 22-Feb-08 | 85 | 2120 | 2090 | 2080 | 2097 | 0.42 | 170 | 165 | 169 | 168 | 91.99 | 213 | 218 | 215 | 215 | 89.73 |
| 24-Feb-08 | 87 | 2080 | 1920 | 1910 | 1970 | 0.39 | 207 | 205 | 202 | 205 | 89.61 | 294 | 303 | 296 | 298 | 84.89 |
| 26-Feb-08 | 89 | 2080 | 2170 | 2120 | 2123 | 0.42 | 239 | 229 | 233 | 234 | 89.00 | 252 | 254 | 252 | 253 | 88.10 |
| 01-Mar-08 | 93 | 2160 | 2160 | 2190 | 2170 | 0.43 | 234 | 227 | 230 | 230 | 89.39 | 233 | 338 | 344 | 305 | 85.94 |

Table A.1 (Continued)

| Date | Days | Influent COD (mg/L) | | | | OLR | Effluent COD M-UASB (mg/L) | | | | Rem. | Effluent COD T-UASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | (g COD/L/.d) | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | | |
| 05-Mar-08 | 97 | 1980 | 2060 | 1990 | 2010 | 0.50 | 319 | 317 | 316 | 317 | 84.21 | 385 | 384 | 380 | 383 | 80.95 |
| 09-Mar-08 | 101 | 2020 | 2040 | 2010 | 2023 | 0.51 | 252 | 242 | 249 | 248 | 87.76 | 313 | 305 | 305 | 308 | 84.79 |
| 11-Mar-08 | 103 | 2120 | 2100 | 2000 | 2073 | 0.52 | 244 | 259 | 258 | 254 | 87.77 | 371 | 362 | 364 | 366 | 82.36 |
| 13-Mar-08 | 105 | 2010 | 2000 | 2070 | 2027 | 0.51 | 223 | 227 | 226 | 225 | 88.88 | 324 | 312 | 319 | 318 | 84.29 |
| 15-Mar-08 | 107 | 1990 | 2070 | 1990 | 2017 | 0.50 | 239 | 251 | 248 | 246 | 87.80 | 362 | 378 | 372 | 371 | 81.62 |
| 17-Mar-08 | 109 | 2030 | 1950 | 1910 | 1963 | 0.49 | 260 | 253 | 267 | 260 | 86.76 | 369 | 376 | 362 | 369 | 81.21 |
| 25-Mar-08 | 117 | 2010 | 2020 | 2000 | 2010 | 0.50 | 1248 | 1255 | 1260 | 1254 | 37.60 | 343 | 341 | 347 | 344 | 82.90 |
| 29-Mar-08 | 121 | 2050 | 2040 | 2020 | 2037 | 0.51 | 816 | 833 | 824 | 824 | 59.53 | 386 | 386 | 387 | 386 | 81.03 |
| 02-Apr-08 | 125 | 1890 | 1950 | 1980 | 1940 | 0.49 | 849 | 840 | 841 | 843 | 56.53 | 334 | 318 | 330 | 327 | 83.13 |
| 06-Apr-08 | 129 | 2030 | 2080 | 2020 | 2043 | 0.51 | 628 | 629 | 827 | 695 | 66.00 | 297 | 313 | 300 | 303 | 85.15 |
| 10-Apr-08 | 133 | 1880 | 1910 | 1910 | 1900 | 0.48 | 549 | 546 | 546 | 547 | 71.21 | 274 | 266 | 271 | 270 | 85.77 |
| 14-Apr-08 | 137 | 1980 | 1990 | 1950 | 1973 | 0.49 | 479 | 463 | 571 | 504 | 74.44 | 297 | 316 | 310 | 308 | 84.41 |
| 18-Apr-08 | 141 | 1850 | 1840 | 1870 | 1853 | 0.46 | 350 | 358 | 352 | 353 | 80.94 | 248 | 231 | 232 | 237 | 87.21 |
| 22-Apr-08 | 145 | 1990 | 2010 | 1940 | 1980 | 0.50 | 245 | 267 | 350 | 287 | 85.49 | 313 | 317 | 320 | 317 | 84.01 |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | | |
| 27-Apr-08 | 150 | 1960 | 1990 | 1980 | 1977 | 0.66 | 393 | 309 | 603 | 435 | 77.99 | 333 | 330 | 331 | 331 | 83.24 |
| 29-Apr-08 | 152 | 1970 | 1960 | 1950 | 1960 | 0.65 | 542 | 556 | 543 | 547 | 72.09 | 363 | 368 | 365 | 365 | 81.36 |
| 01-May-08 | 154 | 1950 | 1930 | 1920 | 1933 | 0.64 | 495 | 501 | 494 | 497 | 74.31 | 328 | 332 | 335 | 332 | 82.84 |
| 05-May-08 | 158 | 1830 | 1850 | 1830 | 1837 | 0.61 | 385 | 381 | 384 | 383 | 79.13 | 280 | 281 | 285 | 282 | 84.65 |
| 07-May-08 | 160 | 1780 | 1880 | 1860 | 1840 | 0.61 | 402 | 391 | 390 | 394 | 78.57 | 331 | 330 | 321 | 327 | 82.21 |

Table A.1 (Continued)

| Date | Days | Influent COD (mg/L) | | | | OLR | Effluent COD M-UASB (mg/L) | | | | Rem. | Effluent COD T-UASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | (g COD/L/.d) | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| High strength influent; HRT of three days (continued) | | | | | | | | | | | | | | | | |
| 09-May-08 | 162 | 1810 | 1760 | 1750 | 1773 | 0.59 | 359 | 363 | 363 | 362 | 79.61 | 428 | 412 | 415 | 418 | 76.41 |
| 11-May-08 | 164 | 1830 | 1860 | 1870 | 1853 | 0.62 | 338 | 339 | 339 | 339 | 81.73 | 412 | 420 | 418 | 417 | 77.52 |
| 13-May-08 | 166 | 1900 | 1910 | 1870 | 1893 | 0.63 | 342 | 356 | 350 | 349 | 81.55 | 488 | 500 | 480 | 489 | 74.15 |
| 15-May-08 | 168 | 1860 | 1890 | 1870 | 1873 | 0.62 | 388 | 394 | 390 | 391 | 79.15 | 490 | 487 | 483 | 487 | 74.02 |
| 17-May-08 | 170 | 1830 | 1860 | 1910 | 1867 | 0.62 | 348 | 345 | 346 | 346 | 81.45 | 477 | 487 | 478 | 481 | 74.25 |
| 20-May-08 | 173 | 1850 | 1890 | 1880 | 1873 | 0.62 | 356 | 370 | 366 | 364 | 80.57 | 468 | 466 | 479 | 471 | 74.86 |
| 22-May-08 | 175 | 1820 | 1830 | 1830 | 1827 | 0.61 | 374 | 382 | 388 | 381 | 79.12 | 465 | 466 | 468 | 466 | 74.47 |
| 24-May-08 | 177 | 1880 | 1850 | 1860 | 1863 | 0.62 | 380 | 372 | 365 | 372 | 80.02 | 480 | 478 | 477 | 478 | 74.33 |
| 26-May-08 | 179 | 1870 | 1860 | 1890 | 1873 | 0.62 | 380 | 378 | 376 | 378 | 79.82 | 466 | 461 | 468 | 465 | 75.18 |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 1830 | 1880 | 1850 | 1853 | 0.93 | 560 | 551 | 549 | 553 | 70.14 | 590 | 610 | 609 | 603 | 67.46 |
| 30-May-08 | 183 | 1790 | 1820 | 1840 | 1817 | 0.91 | 530 | 523 | 511 | 521 | 71.30 | 710 | 717 | 728 | 718 | 60.46 |
| 01-Jun-08 | 185 | 1830 | 1840 | 1850 | 1840 | 0.92 | 521 | 532 | 525 | 526 | 71.41 | 722 | 732 | 725 | 726 | 60.53 |
| 03-Jun-08 | 187 | 1780 | 1790 | 1810 | 1793 | 0.90 | 490 | 488 | 479 | 486 | 72.92 | 680 | 669 | 673 | 674 | 62.42 |
| 05-Jun-08 | 189 | 1810 | 1850 | 1870 | 1843 | 0.92 | 477 | 478 | 489 | 481 | 73.89 | 640 | 631 | 632 | 634 | 65.59 |
| 07-Jun-08 | 191 | 1890 | 1870 | 1870 | 1877 | 0.94 | 461 | 463 | 468 | 464 | 75.28 | 621 | 618 | 616 | 618 | 67.05 |
| 09-Jun-08 | 193 | 1840 | 1800 | 1810 | 1817 | 0.91 | 460 | 473 | 466 | 466 | 74.33 | 580 | 588 | 578 | 582 | 67.96 |
| 11-Jun-08 | 195 | 1780 | 1820 | 1850 | 1817 | 0.91 | 423 | 431 | 428 | 427 | 76.48 | 560 | 555 | 551 | 555 | 69.43 |
| 13-Jun-08 | 197 | 1790 | 1780 | 1760 | 1777 | 0.89 | 431 | 420 | 422 | 424 | 76.12 | 539 | 553 | 554 | 549 | 69.12 |
| 15-Jun-08 | 199 | 1780 | 1770 | 1760 | 1770 | 0.89 | 421 | 427 | 428 | 425 | 75.97 | 552 | 554 | 553 | 553 | 68.76 |

Table A.2 Influent and effluent COD concentrations, OLR, and COD removal data in the mesophilic and thermophilic HUASB reactors

| Date | Days | Influent COD (mg/L) | | | | OLR | Effluent COD M-HUASB (mg/L) | | | | Rem. | Effluent COD T-HUASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | (g COD/L/.d) | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | | |
| 31-Jan-08 | 63 | 520 | 524 | 514 | 519 | 0.17 | 78 | 78 | 76 | 77 | 85.11 | 285 | 280 | 278 | 281 | 45.89 |
| 02-Feb-08 | 65 | 504 | 531 | 501 | 512 | 0.17 | 87 | 81 | 85 | 84 | 83.53 | 232 | 230 | 226 | 229 | 55.21 |
| 04-Feb-08 | 67 | 521 | 502 | 505 | 509 | 0.17 | 66 | 70 | 68 | 68 | 86.65 | 188 | 189 | 192 | 190 | 62.76 |
| 06-Feb-08 | 69 | 506 | 507 | 516 | 510 | 0.17 | 49 | 49 | 51 | 50 | 90.26 | 157 | 160 | 159 | 159 | 68.87 |
| 10-Feb-08 | 73 | 505 | 512 | 500 | 506 | 0.17 | 39 | 43 | 42 | 41 | 91.83 | 182 | 175 | 178 | 178 | 64.73 |
| 12-Feb-08 | 75 | 499 | 508 | 501 | 503 | 0.17 | 45 | 44 | 40 | 43 | 91.45 | 168 | 159 | 162 | 163 | 67.57 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | | |
| 14-Feb-08 | 77 | 2110 | 2160 | 2150 | 2140 | 0.43 | 116 | 126 | 124 | 122 | 94.30 | 251 | 251 | 254 | 252 | 88.22 |
| 16-Feb-08 | 79 | 2200 | 2240 | 2210 | 2217 | 0.44 | 109 | 118 | 115 | 114 | 94.86 | 266 | 252 | 160 | 226 | 89.80 |
| 18-Feb-08 | 81 | 2200 | 2140 | 2150 | 2163 | 0.43 | 130 | 122 | 125 | 126 | 94.19 | 273 | 273 | 274 | 273 | 87.37 |
| 20-Feb-08 | 83 | 2150 | 2130 | 2130 | 2137 | 0.43 | 128 | 126 | 120 | 125 | 94.17 | 300 | 302 | 299 | 300 | 85.94 |
| 22-Feb-08 | 85 | 2120 | 2090 | 2080 | 2097 | 0.42 | 145 | 146 | 152 | 148 | 92.96 | 311 | 314 | 316 | 314 | 85.04 |
| 24-Feb-08 | 87 | 2080 | 1920 | 1910 | 1970 | 0.39 | 131 | 135 | 134 | 133 | 93.23 | 298 | 302 | 303 | 301 | 84.72 |
| 26-Feb-08 | 89 | 2080 | 2170 | 2120 | 2123 | 0.42 | 139 | 130 | 139 | 136 | 93.59 | 296 | 294 | 294 | 295 | 86.12 |
| 01-Mar-08 | 93 | 2160 | 2160 | 2190 | 2170 | 0.43 | 163 | 153 | 157 | 158 | 92.73 | 288 | 279 | 283 | 283 | 86.94 |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | | |
| 05-Mar-08 | 97 | 1980 | 2060 | 1990 | 2010 | 0.50 | 193 | 194 | 192 | 193 | 90.40 | 558 | 558 | 552 | 556 | 72.34 |
| 09-Mar-08 | 101 | 2020 | 2040 | 2010 | 2023 | 0.51 | 174 | 176 | 180 | 177 | 91.27 | 561 | 557 | 541 | 553 | 72.67 |
| 11-Mar-08 | 103 | 2120 | 2100 | 2000 | 2073 | 0.52 | 244 | 251 | 247 | 247 | 88.07 | 423 | 421 | 417 | 420 | 79.73 |
| 13-Mar-08 | 105 | 2010 | 2000 | 2070 | 2027 | 0.51 | 209 | 208 | 209 | 209 | 89.70 | 417 | 417 | 412 | 415 | 79.51 |
| 15-Mar-08 | 107 | 1990 | 2070 | 1990 | 2017 | 0.50 | 180 | 187 | 182 | 183 | 90.93 | 422 | 411 | 421 | 418 | 79.27 |
| 17-Mar-08 | 109 | 2030 | 1950 | 1910 | 1963 | 0.49 | 198 | 196 | 199 | 198 | 89.93 | 412 | 410 | 414 | 412 | 79.02 |
| 25-Mar-08 | 117 | 2010 | 2020 | 2000 | 2010 | 0.50 | 221 | 214 | 228 | 221 | 89.00 | 400 | 399 | 422 | 407 | 79.75 |
| 29-Mar-08 | 121 | 2050 | 2040 | 2020 | 2037 | 0.51 | 233 | 232 | 231 | 232 | 88.61 | 330 | 335 | 344 | 336 | 83.49 |
| 02-Apr-08 | 125 | 1890 | 1950 | 1980 | 1940 | 0.49 | 197 | 194 | 195 | 195 | 89.93 | 308 | 310 | 317 | 312 | 83.93 |
| 06-Apr-08 | 129 | 2030 | 2080 | 2020 | 2043 | 0.51 | 227 | 221 | 226 | 225 | 89.00 | 342 | 348 | 350 | 347 | 83.03 |
| 10-Apr-08 | 133 | 1880 | 1910 | 1910 | 1900 | 0.48 | 181 | 187 | 183 | 184 | 90.33 | 307 | 305 | 301 | 304 | 83.98 |
| 14-Apr-08 | 137 | 1980 | 1990 | 1950 | 1973 | 0.49 | 195 | 185 | 191 | 190 | 90.35 | 329 | 320 | 319 | 323 | 83.65 |

Table A.2 (Continued)

| Date | Days | Influent COD (mg/L) | | | | OLR | Effluent COD M-HUASB (mg/L) | | | | Rem. | Effluent COD T-HUASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | (g COD/L/.d) | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| High strength influent; HRT of four days (continued) | | | | | | | | | | | | | | | | |
| 18-Apr-08 | 141 | 1850 | 1840 | 1870 | 1853 | 0.46 | 227 | 224 | 225 | 225 | 87.84 | 351 | 350 | 344 | 348 | 81.21 |
| 22-Apr-08 | 145 | 1990 | 2010 | 1940 | 1980 | 0.50 | 230 | 231 | 225 | 229 | 88.45 | 344 | 351 | 355 | 350 | 82.32 |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | | |
| 27-Apr-08 | 150 | 1960 | 1990 | 1980 | 1977 | 0.66 | 260 | 254 | 255 | 256 | 87.03 | 568 | 577 | 578 | 574 | 70.94 |
| 29-Apr-08 | 152 | 1970 | 1960 | 1950 | 1960 | 0.65 | 253 | 269 | 256 | 259 | 86.77 | 592 | 593 | 589 | 591 | 69.83 |
| 01-May-08 | 154 | 1950 | 1930 | 1920 | 1933 | 0.64 | 237 | 235 | 230 | 234 | 87.90 | 479 | 475 | 474 | 476 | 75.38 |
| 05-May-08 | 158 | 1830 | 1850 | 1830 | 1837 | 0.61 | 251 | 233 | 240 | 241 | 86.86 | 350 | 349 | 347 | 349 | 81.02 |
| 07-May-08 | 160 | 1780 | 1880 | 1860 | 1840 | 0.61 | 270 | 268 | 265 | 268 | 85.45 | 326 | 320 | 316 | 321 | 82.57 |
| 09-May-08 | 162 | 1810 | 1760 | 1750 | 1773 | 0.59 | 257 | 245 | 246 | 249 | 85.94 | 347 | 348 | 347 | 347 | 80.41 |
| 11-May-08 | 164 | 1830 | 1860 | 1870 | 1853 | 0.62 | 263 | 276 | 271 | 270 | 85.43 | 374 | 375 | 379 | 376 | 79.71 |
| 13-May-08 | 166 | 1900 | 1910 | 1870 | 1893 | 0.63 | 290 | 279 | 282 | 284 | 85.02 | 307 | 305 | 302 | 305 | 83.91 |
| 15-May-08 | 168 | 1860 | 1890 | 1870 | 1873 | 0.62 | 288 | 279 | 283 | 283 | 84.88 | 404 | 410 | 415 | 410 | 78.13 |
| 17-May-08 | 170 | 1830 | 1860 | 1910 | 1867 | 0.62 | 305 | 307 | 299 | 304 | 83.73 | 408 | 410 | 410 | 409 | 78.07 |
| 20-May-08 | 173 | 1850 | 1890 | 1880 | 1873 | 0.62 | 310 | 302 | 301 | 304 | 83.75 | 380 | 389 | 388 | 386 | 79.41 |
| 22-May-08 | 175 | 1820 | 1830 | 1830 | 1827 | 0.61 | 281 | 276 | 288 | 282 | 84.58 | 431 | 421 | 423 | 425 | 76.73 |
| 24-May-08 | 177 | 1880 | 1850 | 1860 | 1863 | 0.62 | 282 | 282 | 276 | 280 | 84.97 | 390 | 395 | 388 | 391 | 79.02 |
| 26-May-08 | 179 | 1870 | 1860 | 1890 | 1873 | 0.62 | 271 | 268 | 265 | 268 | 85.69 | 383 | 380 | 391 | 385 | 79.47 |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 1830 | 1880 | 1850 | 1853 | 0.93 | 288 | 281 | 285 | 285 | 84.64 | 550 | 554 | 531 | 545 | 70.59 |
| 30-May-08 | 183 | 1790 | 1820 | 1840 | 1817 | 0.91 | 290 | 299 | 297 | 295 | 83.74 | 481 | 470 | 476 | 476 | 73.82 |
| 01-Jun-08 | 185 | 1830 | 1840 | 1850 | 1840 | 0.92 | 310 | 318 | 314 | 314 | 82.93 | 489 | 480 | 491 | 487 | 73.55 |
| 03-Jun-08 | 187 | 1780 | 1790 | 1810 | 1793 | 0.90 | 321 | 319 | 312 | 317 | 82.30 | 521 | 498 | 512 | 510 | 71.54 |
| 05-Jun-08 | 189 | 1810 | 1850 | 1870 | 1843 | 0.92 | 361 | 356 | 355 | 357 | 80.61 | 470 | 461 | 455 | 462 | 74.94 |
| 07-Jun-08 | 191 | 1890 | 1870 | 1870 | 1877 | 0.94 | 364 | 374 | 376 | 371 | 80.21 | 488 | 478 | 493 | 486 | 74.09 |
| 09-Jun-08 | 193 | 1840 | 1800 | 1810 | 1817 | 0.91 | 310 | 318 | 309 | 312 | 82.81 | 453 | 444 | 435 | 444 | 75.56 |
| 11-Jun-08 | 195 | 1780 | 1820 | 1850 | 1817 | 0.91 | 308 | 301 | 296 | 302 | 83.39 | 437 | 431 | 427 | 432 | 76.24 |
| 13-Jun-08 | 197 | 1790 | 1780 | 1760 | 1777 | 0.89 | 326 | 313 | 320 | 320 | 82.01 | 441 | 432 | 435 | 436 | 75.46 |
| 15-Jun-08 | 199 | 1780 | 1770 | 1760 | 1770 | 0.89 | 312 | 314 | 310 | 312 | 82.37 | 447 | 455 | 441 | 448 | 74.71 |

Table A.3 Influent and effluent $BOD_5$ concentrations and $BOD_5$ removal data in the mesophilic and thermophilic UASB reactors

| Date | Days | Influent $BOD_5$ (mg/L) | | | | Effluent $BOD_5$ M-UASB (mg/L) | | | | Rem. | Effluent $BOD_5$ T-UASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| Low strength influent; HRT of five days | | | | | | | | | | | | | | | |
| 04-Dec-07 | 5 | 305 | 310 | 318 | 311 | 23 | 25 | 26 | 25 | 92 | 34 | 35 | 37 | 35 | 89 |
| 08-Dec-07 | 9 | 310 | 307 | 279 | 299 | 18 | 21 | 21 | 20 | 93 | 33 | 31 | 30 | 31 | 90 |
| 12-Dec-07 | 13 | 315 | 296 | 301 | 304 | 33 | 45 | 31 | 36 | 88 | 34 | 43 | 40 | 39 | 87 |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | |
| 16-Dec-07 | 17 | 319 | 300 | 299 | 306 | 47 | 53 | 46 | 49 | 84 | 55 | 54 | 51 | 53 | 83 |
| 20-Dec-07 | 21 | 318 | 316 | 312 | 315 | 33 | 25 | 27 | 28 | 91 | 44 | 46 | 38 | 43 | 86 |
| 22-Dec-07 | 23 | 305 | 305 | 304 | 305 | 22 | 20 | 20 | 21 | 93 | 36 | 30 | 33 | 33 | 89 |
| 26-Dec-07 | 27 | 330 | 323 | 341 | 331 | 32 | 24 | 22 | 26 | 92 | 33 | 30 | 38 | 34 | 90 |
| 01-Jan-08 | 33 | 364 | 359 | 361 | 361 | 24 | 25 | 28 | 26 | 93 | 40 | 39 | 38 | 39 | 89 |
| 09-Jan-08 | 41 | 402 | 374 | 383 | 386 | 29 | 27 | 25 | 27 | 93 | 32 | 35 | 38 | 35 | 91 |
| 13-Jan-08 | 45 | 370 | 366 | 358 | 365 | 35 | 33 | 28 | 32 | 91 | 44 | 41 | 39 | 41 | 89 |
| 15-Jan-08 | 47 | 324 | 367 | 349 | 347 | 36 | 31 | 25 | 31 | 91 | 51 | 41 | 45 | 46 | 87 |
| 21-Jan-08 | 53 | 357 | 355 | 346 | 353 | 34 | 38 | 31 | 34 | 90 | 43 | 48 | 41 | 44 | 88 |
| 23-Jan-08 | 55 | 362 | 348 | 345 | 352 | 41 | 34 | 31 | 35 | 90 | 35 | 31 | 27 | 31 | 91 |
| 27-Jan-08 | 59 | 321 | 343 | 336 | 333 | 27 | 28 | 24 | 26 | 92 | 27 | 35 | 31 | 31 | 91 |
| 29-Jan-08 | 61 | 310 | 327 | 316 | 318 | 34 | 40 | 34 | 36 | 89 | 28 | 31 | 38 | 32 | 90 |
| 02-Feb-08 | 65 | 318 | 323 | 344 | 328 | 34 | 24 | 25 | 28 | 92 | 34 | 30 | 41 | 35 | 89 |
| 04-Feb-08 | 67 | 319 | 322 | 334 | 325 | 16 | 20 | 22 | 19 | 94 | 24 | 28 | 24 | 25 | 92 |
| 06-Feb-08 | 69 | 377 | 383 | 384 | 381 | 13 | 16 | 14 | 14 | 96 | 18 | 24 | 30 | 24 | 94 |
| 10-Feb-08 | 73 | 388 | 383 | 367 | 379 | 25 | 22 | 16 | 21 | 94 | 34 | 27 | 33 | 31 | 92 |
| 12-Feb-08 | 75 | 374 | 396 | 380 | 383 | 21 | 17 | 22 | 20 | 95 | 24 | 29 | 31 | 28 | 93 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | |
| 16-Feb-08 | 79 | 1581 | 1632 | 1588 | 1600 | 43 | 40 | 42 | 42 | 97 | 72 | 77 | 81 | 77 | 95 |
| 20-Feb-08 | 83 | 1512 | 1561 | 1604 | 1559 | 80 | 67 | 55 | 68 | 96 | 132 | 123 | 111 | 122 | 92 |
| 24-Feb-08 | 87 | 1405 | 1435 | 1440 | 1427 | 72 | 90 | 73 | 78 | 95 | 166 | 164 | 148 | 159 | 89 |
| 26-Feb-08 | 89 | 1450 | 1514 | 1534 | 1499 | 88 | 71 | 77 | 79 | 95 | 144 | 148 | 152 | 148 | 90 |
| 01-Mar-08 | 93 | 1525 | 1612 | 1590 | 1576 | 75 | 73 | 63 | 70 | 96 | 136 | 172 | 179 | 163 | 90 |

Table A.3 (Continued)

| Date | Days | Influent $BOD_5$ (mg/L) | | | | Effluent $BOD_5$ M-UASB (mg/L) | | | | Rem. | Effluent $BOD_5$ T-UASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | |
| 05-Mar-08 | 97 | 1497 | 1513 | 1523 | 1511 | 122 | 134 | 131 | 129 | 91 | 213 | 207 | 204 | 208 | 86 |
| 09-Mar-08 | 101 | 1454 | 1489 | 1487 | 1477 | 146 | 140 | 147 | 144 | 90 | 221 | 225 | 213 | 220 | 85 |
| 13-Mar-08 | 105 | 1487 | 1560 | 1573 | 1540 | 112 | 107 | 102 | 107 | 93 | 214 | 159 | 169 | 181 | 88 |
| 17-Mar-08 | 109 | 1482 | 1463 | 1394 | 1446 | 133 | 119 | 112 | 121 | 92 | 251 | 241 | 192 | 228 | 84 |
| 29-Mar-08 | 121 | 1415 | 1428 | 1394 | 1412 | 392 | 383 | 371 | 382 | 73 | 220 | 224 | 197 | 214 | 85 |
| 06-Apr-08 | 129 | 1360 | 1414 | 1394 | 1389 | 295 | 315 | 380 | 330 | 76 | 172 | 185 | 183 | 180 | 87 |
| 14-Apr-08 | 137 | 1366 | 1433 | 1365 | 1388 | 216 | 181 | 240 | 212 | 85 | 175 | 180 | 158 | 171 | 88 |
| 18-Apr-08 | 141 | 1401 | 1388 | 1397 | 1395 | 123 | 128 | 118 | 123 | 91 | 188 | 178 | 167 | 178 | 87 |
| 22-Apr-08 | 145 | 1401 | 1456 | 1366 | 1408 | 105 | 109 | 137 | 117 | 92 | 191 | 197 | 208 | 198 | 86 |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | |
| 29-Apr-08 | 152 | 1438 | 1490 | 1521 | 1483 | 189 | 201 | 213 | 201 | 86 | 195 | 202 | 234 | 210 | 86 |
| 01-May-08 | 154 | 1367 | 1388 | 1371 | 1375 | 185 | 181 | 177 | 181 | 87 | 222 | 218 | 211 | 217 | 84 |
| 05-May-08 | 158 | 1409 | 1459 | 1425 | 1431 | 185 | 171 | 157 | 171 | 88 | 248 | 252 | 260 | 253 | 82 |
| 09-May-08 | 162 | 1385 | 1367 | 1348 | 1367 | 176 | 171 | 163 | 170 | 88 | 257 | 251 | 245 | 251 | 82 |
| 13-May-08 | 166 | 1344 | 1365 | 1351 | 1353 | 171 | 181 | 183 | 178 | 87 | 268 | 256 | 267 | 264 | 81 |
| 15-May-08 | 168 | 1336 | 1318 | 1321 | 1325 | 198 | 173 | 187 | 186 | 86 | 274 | 248 | 251 | 258 | 81 |
| 17-May-08 | 170 | 1208 | 1283 | 1280 | 1257 | 181 | 183 | 166 | 177 | 86 | 281 | 302 | 277 | 287 | 77 |
| 20-May-08 | 173 | 1184 | 1247 | 1203 | 1212 | 153 | 167 | 187 | 169 | 86 | 285 | 247 | 235 | 256 | 79 |
| 24-May-08 | 177 | 1222 | 1277 | 1246 | 1248 | 160 | 190 | 183 | 177 | 86 | 272 | 263 | 267 | 267 | 79 |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 1281 | 1272 | 1288 | 1280 | 252 | 242 | 236 | 244 | 81 | 330 | 311 | 292 | 311 | 76 |
| 01-Jun-08 | 185 | 1186 | 1211 | 1199 | 1198 | 301 | 288 | 280 | 290 | 76 | 314 | 300 | 326 | 313 | 74 |
| 05-Jun-08 | 189 | 1231 | 1314 | 1290 | 1278 | 196 | 182 | 201 | 193 | 85 | 283 | 299 | 278 | 287 | 78 |
| 09-Jun-08 | 193 | 1270 | 1260 | 1285 | 1272 | 212 | 208 | 200 | 207 | 84 | 319 | 300 | 283 | 301 | 76 |
| 13-Jun-08 | 197 | 1243 | 1223 | 1255 | 1240 | 211 | 185 | 190 | 195 | 84 | 329 | 304 | 310 | 314 | 75 |
| 15-Jun-08 | 199 | 1264 | 1186 | 1162 | 1204 | 177 | 195 | 183 | 185 | 85 | 298 | 283 | 299 | 293 | 76 |

Table A.4 Influent and effluent $BOD_5$ concentrations and $BOD_5$ removal data in the mesophilic and thermophilic HUASB reactors

| Date | Days | Influent $BOD_5$ (mg/L) | | | | Effluent $BOD_5$ M-HUASB (mg/L) | | | | Rem. | Effluent $BOD_5$ T-HUASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | |
| 04-Feb-08 | 67 | 319 | 322 | 334 | 325 | 29 | 37 | 32 | 33 | 90 | 101 | 98 | 92 | 97 | 70 |
| 06-Feb-08 | 69 | 377 | 383 | 384 | 381 | 34 | 38 | 31 | 34 | 91 | 83 | 78 | 81 | 81 | 79 |
| 10-Feb-08 | 73 | 388 | 383 | 367 | 379 | 18 | 22 | 20 | 20 | 95 | 78 | 85 | 72 | 78 | 79 |
| 12-Feb-08 | 75 | 374 | 396 | 380 | 383 | 23 | 21 | 18 | 21 | 95 | 87 | 72 | 73 | 77 | 80 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | |
| 16-Feb-08 | 79 | 1581 | 1632 | 1588 | 1600 | 40 | 44 | 36 | 40 | 97 | 179 | 170 | 164 | 171 | 89 |
| 20-Feb-08 | 83 | 1512 | 1561 | 1604 | 1559 | 47 | 41 | 39 | 42 | 97 | 167 | 159 | 161 | 162 | 90 |
| 24-Feb-08 | 87 | 1405 | 1435 | 1440 | 1427 | 55 | 51 | 47 | 51 | 96 | 148 | 143 | 142 | 144 | 90 |
| 26-Feb-08 | 89 | 1450 | 1514 | 1534 | 1499 | 58 | 45 | 51 | 51 | 97 | 135 | 147 | 131 | 138 | 91 |
| 01-Mar-08 | 93 | 1525 | 1612 | 1590 | 1576 | 78 | 69 | 66 | 71 | 95 | 142 | 141 | 136 | 140 | 91 |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | |
| 05-Mar-08 | 97 | 1497 | 1513 | 1523 | 1511 | 99 | 96 | 87 | 94 | 94 | 271 | 266 | 263 | 267 | 82 |
| 09-Mar-08 | 101 | 1454 | 1489 | 1487 | 1477 | 85 | 79 | 77 | 81 | 95 | 264 | 256 | 238 | 253 | 83 |
| 13-Mar-08 | 105 | 1487 | 1560 | 1573 | 1540 | 98 | 106 | 94 | 99 | 94 | 204 | 183 | 173 | 187 | 88 |
| 17-Mar-08 | 109 | 1482 | 1463 | 1394 | 1446 | 89 | 88 | 92 | 90 | 94 | 202 | 209 | 215 | 209 | 86 |
| 29-Mar-08 | 121 | 1415 | 1428 | 1394 | 1412 | 119 | 125 | 116 | 120 | 92 | 149 | 147 | 182 | 159 | 89 |
| 06-Apr-08 | 129 | 1360 | 1414 | 1394 | 1389 | 116 | 104 | 115 | 112 | 92 | 150 | 164 | 179 | 164 | 88 |
| 14-Apr-08 | 137 | 1366 | 1433 | 1365 | 1388 | 94 | 87 | 82 | 88 | 94 | 125 | 131 | 118 | 125 | 91 |
| 18-Apr-08 | 141 | 1401 | 1388 | 1397 | 1395 | 84 | 88 | 91 | 88 | 94 | 123 | 127 | 119 | 123 | 91 |
| 22-Apr-08 | 145 | 1401 | 1456 | 1366 | 1408 | 99 | 88 | 83 | 90 | 94 | 110 | 144 | 124 | 126 | 91 |

Table A.4 (Continued)

| Date | Days | Influent $BOD_5$ (mg/L) | | | | Effluent $BOD_5$ M-HUASB (mg/L) | | | | Rem. | Effluent $BOD_5$ T-HUASB (mg/L) | | | | Rem. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | % | S1 | S2 | S3 | Ave. | % |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | |
| 29-Apr-08 | 152 | 1438 | 1490 | 1521 | 1483 | 104 | 89 | 115 | 103 | 93 | 198 | 196 | 206 | 200 | 87 |
| 01-May-08 | 154 | 1367 | 1388 | 1371 | 1375 | 88 | 97 | 107 | 97 | 93 | 166 | 161 | 151 | 159 | 88 |
| 05-May-08 | 158 | 1409 | 1459 | 1425 | 1431 | 120 | 100 | 96 | 106 | 93 | 133 | 141 | 121 | 132 | 91 |
| 09-May-08 | 162 | 1385 | 1367 | 1348 | 1367 | 121 | 103 | 111 | 111 | 92 | 125 | 138 | 144 | 136 | 90 |
| 13-May-08 | 166 | 1344 | 1365 | 1351 | 1353 | 109 | 111 | 105 | 108 | 92 | 135 | 134 | 143 | 137 | 90 |
| 15-May-08 | 168 | 1336 | 1318 | 1321 | 1325 | 127 | 114 | 108 | 116 | 91 | 141 | 185 | 158 | 161 | 88 |
| 17-May-08 | 170 | 1208 | 1283 | 1280 | 1257 | 137 | 135 | 120 | 131 | 90 | 135 | 168 | 144 | 149 | 88 |
| 20-May-08 | 173 | 1184 | 1247 | 1203 | 1212 | 130 | 136 | 123 | 130 | 89 | 163 | 171 | 159 | 165 | 86 |
| 24-May-08 | 177 | 1222 | 1277 | 1246 | 1248 | 135 | 133 | 135 | 134 | 89 | 172 | 174 | 175 | 173 | 86 |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 1281 | 1272 | 1288 | 1280 | 141 | 124 | 120 | 128 | 90 | 275 | 294 | 260 | 276 | 78 |
| 01-Jun-08 | 185 | 1186 | 1211 | 1199 | 1198 | 163 | 146 | 160 | 156 | 87 | 233 | 226 | 236 | 231 | 81 |
| 05-Jun-08 | 189 | 1231 | 1314 | 1290 | 1278 | 146 | 117 | 124 | 129 | 90 | 185 | 193 | 209 | 196 | 85 |
| 09-Jun-08 | 193 | 1270 | 1260 | 1285 | 1272 | 118 | 95 | 108 | 107 | 92 | 199 | 204 | 178 | 194 | 85 |
| 13-Jun-08 | 197 | 1243 | 1223 | 1255 | 1240 | 108 | 100 | 99 | 102 | 92 | 216 | 194 | 200 | 204 | 84 |
| 15-Jun-08 | 199 | 1264 | 1186 | 1162 | 1204 | 115 | 100 | 112 | 109 | 91 | 215 | 214 | 185 | 205 | 83 |

Table A.5 Influent and effluent $NH_3$-N concentrations data in the UASB and HUASB reactors

| Date | Days | Influent $NH_3$-N (mg/L) | | | | Effluent $NH_3$-N M-UASB (mg/L) | | | | Effluent $NH_3$-N T-UASB (mg/L) | | | | Effluent $NH_3$-N M-HUASB (mg/L) | | | | Effluent $NH_3$-N T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave |
| Low strength influent; HRT of five days | | | | | | | | | | | | | | | | | | | | | |
| 02-Dec-07 | 3 | 3.4 | 2.6 | 3.5 | 3.2 | 12.8 | 12.5 | 13.8 | 13.0 | 17.6 | 11.7 | 11.9 | 13.7 | | | | | | | | |
| 04-Dec-07 | 5 | 2.4 | 3.3 | 3.2 | 3.0 | 12.7 | 12.5 | 12.8 | 12.7 | 12.3 | 12.6 | 12.5 | 12.5 | | | | | | | | |
| 08-Dec-07 | 9 | 3.7 | 2.5 | 3.2 | 3.1 | 12.2 | 11.9 | 12.0 | 12.0 | 11.4 | 11.5 | 11.6 | 11.5 | | | | | | | | |
| 10-Dec-07 | 11 | 3.5 | 3.4 | 3.0 | 3.3 | 12.8 | 13.2 | 13.1 | 13.0 | 11.9 | 12.1 | 11.8 | 11.9 | | | | | | | | |
| 12-Dec-07 | 13 | 3.6 | 3.7 | 3.8 | 3.7 | 11.5 | 11.2 | 11.8 | 11.5 | 8.5 | 8.7 | 8.3 | 8.5 | | | | | | | | |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | | | | | | | |
| 16-Dec-07 | 17 | 3.8 | 4.4 | 4.0 | 4.1 | 4.6 | 4.5 | 4.5 | 4.5 | 4.2 | 4.1 | 4.1 | 4.1 | | | | | | | | |
| 18-Dec-07 | 19 | 2.4 | 2.5 | 2.5 | 2.5 | 5.9 | 6.2 | 6.1 | 6.1 | 5.8 | 4.9 | 5.6 | 5.4 | | | | | | | | |
| 20-Dec-07 | 21 | 2.7 | 3.1 | 3.0 | 2.9 | 6.7 | 6.4 | 6.3 | 6.5 | 5.0 | 5.6 | 5.3 | 5.3 | | | | | | | | |
| 22-Dec-07 | 23 | 2.6 | 3.6 | 3.0 | 3.1 | 6.6 | 7.4 | 6.2 | 6.7 | 3.6 | 4.2 | 3.9 | 3.9 | | | | | | | | |
| 24-Dec-07 | 25 | 6.3 | 5.5 | 5.8 | 5.9 | 9.3 | 10.5 | 11.8 | 10.5 | 7.5 | 6.8 | 6.6 | 7.0 | | | | | | | | |
| 26-Dec-07 | 27 | 5.4 | 5.1 | 6.3 | 5.6 | 10.3 | 9.8 | 10.2 | 10.1 | 8.5 | 8.7 | 8.4 | 8.5 | | | | | | | | |
| 28-Dec-07 | 29 | 6.0 | 5.9 | 6.0 | 6.0 | 9.6 | 12.6 | 10.2 | 10.8 | 9.4 | 10.2 | 9.7 | 9.8 | | | | | | | | |
| 01-Jan-08 | 33 | 4.3 | 4.0 | 4.8 | 4.4 | 9.9 | 10.3 | 10.7 | 10.3 | 6.3 | 6.8 | 6.9 | 6.7 | | | | | | | | |
| 03-Jan-08 | 35 | 4.8 | 4.6 | 4.4 | 4.6 | 10.0 | 10.5 | 10.8 | 10.4 | 7.5 | 7.8 | 7.7 | 7.7 | | | | | | | | |
| 07-Jan-08 | 39 | 4.9 | 5.5 | 4.7 | 5.0 | 9.6 | 9.9 | 9.1 | 9.5 | 6.5 | 6.9 | 7.2 | 6.9 | | | | | | | | |
| 09-Jan-08 | 41 | 5.1 | 5.0 | 4.8 | 5.0 | 9.0 | 8.5 | 8.2 | 8.6 | 6.6 | 6.3 | 7.0 | 6.6 | | | | | | | | |
| 11-Jan-08 | 43 | 5.5 | 5.2 | 5.1 | 5.3 | 8.8 | 8.7 | 8.5 | 8.7 | 8.8 | 8.1 | 8.2 | 8.4 | | | | | | | | |
| 13-Jan-08 | 45 | 4.8 | 4.8 | 5.1 | 4.9 | 8.9 | 8.8 | 9.4 | 9.0 | 7.6 | 7.4 | 7.7 | 7.6 | | | | | | | | |
| 15-Jan-08 | 47 | 4.5 | 4.6 | 4.8 | 4.6 | 7.8 | 8.1 | 8.5 | 8.1 | 7.5 | 8.2 | 7.7 | 7.8 | | | | | | | | |
| 17-Jan-08 | 49 | 4.7 | 4.6 | 4.4 | 4.6 | 8.5 | 9.3 | 8.8 | 8.9 | 7.9 | 8.5 | 8.7 | 8.4 | | | | | | | | |
| 21-Jan-08 | 53 | 4.9 | 5.1 | 5.2 | 5.1 | 8.7 | 8.9 | 8.4 | 8.7 | 8.5 | 8.1 | 8.7 | 8.4 | | | | | | | | |
| 23-Jan-08 | 55 | 4.4 | 4.7 | 4.5 | 4.5 | 9.1 | 9.3 | 9.8 | 9.4 | 7.4 | 7.5 | 7.3 | 7.4 | | | | | | | | |
| 27-Jan-08 | 59 | 4.5 | 4.5 | 4.6 | 4.5 | 9.2 | 8.8 | 8.9 | 9.0 | 7.7 | 7.5 | 7.6 | 7.6 | | | | | | | | |

Table A.5 (Continued)

| Date | Days | Influent $NH_3$-N (mg/L) | | | | Effluent $NH_3$-N M-UASB (mg/L) | | | | Effluent $NH_3$-N T-UASB (mg/L) | | | | Effluent $NH_3$-N M-HUASB (mg/L) | | | | Effluent $NH_3$-N T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave |
| Low strength influent; HRT of three days (continued) | | | | | | | | | | | | | | | | | | | | | |
| 31-Jan-08 | 63 | 5.1 | 5.3 | 5.0 | 5.1 | 8.7 | 8.8 | 8.6 | 8.7 | 7.9 | 7.3 | 7.5 | 7.6 | 18.9 | 19.0 | 18.9 | 18.9 | 13.2 | 13.6 | 13.5 | 13.4 |
| 04-Feb-08 | 67 | 4.4 | 4.7 | 4.8 | 4.6 | 8.9 | 8.3 | 8.9 | 8.7 | 7.4 | 8.1 | 7.3 | 7.6 | 19.0 | 18.2 | 19.4 | 18.9 | 14.4 | 13.8 | 14.2 | 14.1 |
| 10-Feb-08 | 73 | 4.9 | 4.8 | 4.6 | 4.8 | 8.8 | 8.4 | 9.1 | 8.8 | 7.7 | 7.8 | 7.9 | 7.8 | 19.5 | 19.3 | 19.4 | 19.4 | 13.7 | 13.6 | 14.0 | 13.8 |
| 12-Feb-08 | 75 | 4.6 | 4.8 | 5.0 | 4.8 | 9.1 | 9.2 | 8.8 | 9.0 | 8.1 | 7.9 | 7.7 | 7.9 | 18.7 | 18.1 | 18.5 | 18.4 | 13.5 | 14.3 | 14.0 | 13.9 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | | | | | | | |
| 14-Feb-08 | 77 | 12.4 | 13.2 | 12.3 | 12.6 | 20.3 | 20.2 | 20.2 | 20.2 | 9.3 | 8.3 | 8.9 | 8.8 | 13.9 | 13.7 | 13.6 | 13.7 | 11.6 | 11.5 | 11.4 | 11.5 |
| 16-Feb-08 | 79 | 11.9 | 12.3 | 11.5 | 11.9 | 19.1 | 18.9 | 18.7 | 18.9 | 10.5 | 11.0 | 11.3 | 10.9 | 15.0 | 14.0 | 14.6 | 14.5 | 13.9 | 13.7 | 13.8 | 13.8 |
| 20-Feb-08 | 83 | 13.3 | 13.4 | 13.6 | 13.4 | 19.9 | 20.0 | 20.0 | 20.0 | 13.9 | 14.2 | 14.3 | 14.1 | 13.7 | 14.5 | 14.2 | 14.1 | 16.2 | 17.0 | 16.1 | 16.4 |
| 24-Feb-08 | 87 | 16.0 | 16.4 | 16.3 | 16.2 | 18.9 | 19.7 | 18.8 | 19.1 | 15.2 | 16.0 | 15.7 | 15.6 | 15.6 | 15.3 | 14.9 | 15.3 | 16.0 | 15.7 | 15.3 | 15.7 |
| 01-Mar-08 | 93 | 19.6 | 19.4 | 18.9 | 19.3 | 17.7 | 17.5 | 18.0 | 17.7 | 14.2 | 13.9 | 13.5 | 13.9 | 18.7 | 19.5 | 18.6 | 18.9 | 16.7 | 15.7 | 16.3 | 16.2 |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | | | | | | | |
| 09-Mar-08 | 101 | 16.3 | 16.1 | 16.2 | 16.2 | 15.4 | 15.2 | 15.3 | 15.3 | 11.9 | 12.0 | 12.2 | 12.0 | 16.5 | 16.3 | 15.8 | 16.2 | 15.7 | 15.6 | 15.8 | 15.7 |
| 13-Mar-08 | 105 | 16.2 | 16.0 | 16.3 | 16.2 | 16.3 | 16.2 | 16.6 | 16.4 | 14.0 | 13.9 | 13.9 | 13.9 | 17.8 | 18.4 | 17.8 | 18.0 | 18.0 | 17.1 | 17.2 | 17.4 |
| 17-Mar-08 | 109 | 15.2 | 15.7 | 16.0 | 15.6 | 17.5 | 17.5 | 17.2 | 17.4 | 13.8 | 13.3 | 13.0 | 13.4 | 17.5 | 16.9 | 17.7 | 17.4 | 15.1 | 16.3 | 15.6 | 15.7 |
| 29-Mar-08 | 121 | 15.0 | 14.4 | 14.8 | 14.7 | 14.8 | 14.7 | 14.6 | 14.7 | 12.9 | 12.3 | 13.1 | 12.8 | 18.6 | 18.4 | 18.2 | 18.4 | 16.3 | 16.1 | 16.0 | 16.1 |
| 06-Apr-08 | 129 | 14.6 | 14.4 | 14.2 | 14.4 | 13.3 | 13.7 | 13.6 | 13.5 | 11.8 | 11.7 | 11.9 | 11.8 | 19.1 | 19.0 | 19.2 | 19.1 | 14.1 | 14.2 | 14.4 | 14.2 |
| 14-Apr-08 | 137 | 14.4 | 14.3 | 14.3 | 14.3 | 12.9 | 12.6 | 12.6 | 12.7 | 13.7 | 13.8 | 14.0 | 13.8 | 18.6 | 18.5 | 18.9 | 18.7 | 14.3 | 13.5 | 14.0 | 13.9 |
| 22-Apr-08 | 145 | 12.5 | 13.1 | 12.5 | 12.7 | 15.9 | 15.7 | 15.2 | 15.6 | 12.9 | 12.7 | 13.2 | 12.9 | 18.6 | 18.5 | 18.4 | 18.5 | 13.8 | 14.1 | 13.5 | 13.8 |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | | | | | | | |
| 29-Apr-08 | 152 | 12.6 | 12.7 | 12.1 | 12.5 | 13.5 | 14.0 | 14.3 | 14.0 | 13.7 | 13.5 | 13.0 | 13.4 | 17.8 | 17.9 | 18.1 | 17.9 | 12.7 | 12.8 | 13.2 | 12.9 |
| 05-May-08 | 158 | 12.1 | 12.4 | 12.5 | 12.3 | 14.2 | 14.5 | 14.6 | 14.4 | 13.5 | 13.9 | 13.8 | 13.7 | 17.8 | 17.8 | 17.7 | 17.8 | 13.5 | 13.3 | 13.6 | 13.5 |
| 09-May-08 | 162 | 11.3 | 11.7 | 11.0 | 11.3 | 14.9 | 14.7 | 14.8 | 14.8 | 13.7 | 13.8 | 14.0 | 13.8 | 17.5 | 17.9 | 17.8 | 17.7 | 13.8 | 13.4 | 13.0 | 13.4 |
| 15-May-08 | 168 | 12.4 | 11.5 | 11.6 | 11.8 | 15.5 | 16.3 | 16.0 | 15.9 | 13.6 | 13.8 | 14.0 | 13.8 | 16.7 | 16.8 | 17.0 | 16.8 | 13.9 | 14.3 | 13.5 | 13.9 |
| 17-May-08 | 170 | 11.8 | 11.5 | 11.5 | 11.6 | 16.7 | 16.4 | 17.2 | 16.8 | 13.2 | 13.8 | 13.2 | 13.4 | 17.5 | 16.6 | 16.7 | 16.9 | 14.3 | 14.0 | 14.0 | 14.1 |
| 20-May-08 | 173 | 12.6 | 12.9 | 12.3 | 12.6 | 15.7 | 15.6 | 15.4 | 15.6 | 14.1 | 13.3 | 13.8 | 13.7 | 17.3 | 17.4 | 16.8 | 17.2 | 14.1 | 13.8 | 14.6 | 14.2 |
| 24-May-08 | 177 | 12.7 | 12.8 | 12.8 | 12.8 | 16.2 | 15.8 | 15.4 | 15.8 | 13.8 | 14.2 | 13.4 | 13.8 | 17.1 | 17.4 | 17.5 | 17.3 | 14.7 | 14.6 | 14.6 | 14.6 |
| 26-May-08 | 179 | 11.7 | 11.5 | 12.0 | 11.7 | 16.0 | 16.1 | 16.5 | 16.2 | 14.2 | 13.9 | 13.9 | 14.0 | 16.9 | 17.2 | 17.3 | 17.1 | 14.7 | 14.8 | 14.8 | 14.8 |

Table A.5 (Continued)

| Date | Days | Influent $NH_3$-N (mg/L) | | | | Effluent $NH_3$-N M-UASB (mg/L) | | | | Effluent $NH_3$-N T-UASB (mg/L) | | | | Effluent $NH_3$-N M-HUASB (mg/L) | | | | Effluent $NH_3$-N T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 12.7 | 12.5 | 12.6 | 12.6 | 15.8 | 15.9 | 16.1 | 15.9 | 14.5 | 14.2 | 15.0 | 14.6 | 17.5 | 18.0 | 18.3 | 17.9 | 14.7 | 14.9 | 15.1 | 14.9 |
| 30-May-08 | 183 | 11.5 | 11.4 | 11.8 | 11.6 | 15.3 | 14.5 | 15.7 | 15.2 | 13.9 | 14.0 | 14.4 | 14.1 | 17.9 | 17.1 | 17.6 | 17.5 | 15.0 | 14.8 | 14.3 | 14.7 |
| 01-Jun-08 | 185 | 11.1 | 11.2 | 11.4 | 11.2 | 15.2 | 14.7 | 14.4 | 14.8 | 13.3 | 13.4 | 13.6 | 13.4 | 17.3 | 17.0 | 17.0 | 17.1 | 13.9 | 14.0 | 13.4 | 13.8 |
| 05-Jun-08 | 189 | 10.9 | 11.2 | 11.3 | 11.1 | 13.8 | 13.9 | 14.1 | 13.9 | 13.9 | 13.8 | 13.6 | 13.8 | 16.4 | 16.2 | 16.7 | 16.4 | 14.0 | 13.8 | 13.9 | 13.9 |
| 07-Jun-08 | 191 | 11.8 | 11.8 | 11.5 | 11.7 | 14.4 | 15.0 | 14.4 | 14.6 | 14.3 | 13.9 | 13.5 | 13.9 | 16.1 | 15.8 | 16.6 | 16.2 | 12.7 | 12.8 | 13.0 | 12.8 |
| 09-Jun-08 | 193 | 11.7 | 11.4 | 11.3 | 11.5 | 14.6 | 14.0 | 14.8 | 14.5 | 13.6 | 13.7 | 13.7 | 13.7 | 16.3 | 16.4 | 16.6 | 16.4 | 13.1 | 13.4 | 13.5 | 13.3 |
| 11-Jun-08 | 195 | 11.3 | 10.5 | 11.0 | 10.9 | 15.0 | 14.7 | 14.6 | 14.8 | 12.7 | 13.9 | 13.2 | 13.3 | 16.2 | 16.1 | 15.9 | 16.1 | 13.6 | 12.8 | 14.0 | 13.5 |
| 13-Jun-08 | 197 | 10.0 | 11.2 | 10.5 | 10.6 | 15.0 | 15.1 | 15.3 | 15.1 | 13.4 | 13.2 | 13.3 | 13.3 | 16.0 | 15.9 | 15.9 | 15.9 | 13.8 | 14.3 | 14.6 | 14.2 |
| 15-Jun-08 | 199 | 10.6 | 10.7 | 11.1 | 10.8 | 15.4 | 15.2 | 15.1 | 15.2 | 13.3 | 13.6 | 13.0 | 13.3 | 15.6 | 15.7 | 15.7 | 15.7 | 14.5 | 14.3 | 14.8 | 14.5 |

Table A.6 Influent and effluent $NO_3$-N concentrations data in the UASB and HUASB reactors

| Date | Days | Influent $NO_3$-N (mg/L) | | | | Effluent $NO_3$-N M-UASB (mg/L) | | | | Effluent $NO_3$-N T-UASB (mg/L) | | | | Effluent $NO_3$-N M-HUASB (mg/L) | | | | Effluent $NO_3$-N T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. |
| Low strength influent; HRT of five days | | | | | | | | | | | | | | | | | | | | | |
| 02-Dec-07 | 3 | 0.8 | 0.7 | 0.9 | 0.8 | 0.6 | 0.7 | 0.6 | 0.6 | 0.4 | 0.2 | 0.5 | 0.4 | | | | | | | | |
| 04-Dec-07 | 5 | 0.7 | 0.7 | 0.5 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 0.3 | 0.3 | 0.3 | 0.3 | | | | | | | | |
| 08-Dec-07 | 9 | 0.7 | 0.4 | 1.0 | 0.7 | 0.9 | 0.6 | 0.7 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | | | | | | | | |
| 10-Dec-07 | 11 | 0.5 | 0.7 | 0.6 | 0.6 | 0.3 | 0.5 | 0.4 | 0.4 | 0.1 | 0.1 | 0.2 | 0.1 | | | | | | | | |
| 12-Dec-07 | 13 | 0.7 | 0.8 | 1.1 | 0.9 | 0.6 | 0.7 | 0.4 | 0.6 | 0.2 | 0.1 | 0.3 | 0.2 | | | | | | | | |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | | | | | | | |
| 16-Dec-07 | 17 | 0.3 | 0.4 | 0.2 | 0.3 | 0.4 | 0.5 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | | | | | | | | |
| 18-Dec-07 | 19 | 0.4 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.1 | 0.2 | 0.3 | 0.6 | 0.5 | 0.5 | | | | | | | | |
| 20-Dec-07 | 21 | 0.5 | 0.5 | 0.7 | 0.6 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | | | | | | | | |
| 22-Dec-07 | 23 | 0.8 | 0.8 | 0.7 | 0.8 | 0.6 | 0.7 | 0.7 | 0.7 | 0.9 | 1.1 | 1.0 | 1.0 | | | | | | | | |
| 24-Dec-07 | 25 | 0.7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.0 | 1.0 | 0.8 | 0.9 | | | | | | | | |
| 26-Dec-07 | 27 | 0.8 | 0.9 | 0.9 | 0.9 | 0.7 | 0.7 | 0.9 | 0.8 | 0.9 | 0.8 | 0.8 | 0.8 | | | | | | | | |
| 28-Dec-07 | 29 | 0.7 | 0.9 | 0.9 | 0.8 | 1.0 | 0.7 | 1.0 | 0.9 | 1.0 | 0.9 | 1.1 | 1.0 | | | | | | | | |
| 01-Jan-08 | 33 | 1.2 | 0.9 | 1.2 | 1.1 | 1.2 | 1.0 | 1.0 | 1.1 | 0.9 | 0.9 | 1.0 | 0.9 | | | | | | | | |
| 03-Jan-08 | 35 | 0.6 | 0.7 | 0.6 | 0.6 | 0.4 | 0.5 | 0.6 | 0.5 | 1.1 | 1.3 | 1.0 | 1.1 | | | | | | | | |
| 07-Jan-08 | 39 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.3 | 0.5 | 0.5 | 0.6 | 0.7 | 0.7 | 0.7 | | | | | | | | |
| 09-Jan-08 | 41 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.5 | 0.5 | 0.5 | 0.8 | 0.6 | 0.5 | 0.6 | | | | | | | | |
| 11-Jan-08 | 43 | 0.6 | 0.6 | 0.4 | 0.5 | 0.4 | 0.5 | 0.3 | 0.4 | 0.7 | 0.8 | 0.7 | 0.7 | | | | | | | | |
| 13-Jan-08 | 45 | 0.3 | 0.3 | 0.4 | 0.3 | 0.1 | 0.1 | 0.2 | 0.1 | 0.3 | 0.4 | 0.5 | 0.4 | | | | | | | | |
| 15-Jan-08 | 47 | 0.4 | 0.5 | 0.3 | 0.4 | 0.1 | 0.1 | 0.3 | 0.2 | 0.4 | 0.4 | 0.6 | 0.5 | | | | | | | | |
| 17-Jan-08 | 49 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.1 | 0.2 | 0.2 | 0.5 | 0.3 | 0.3 | 0.4 | | | | | | | | |
| 21-Jan-08 | 53 | 0.3 | 0.4 | 0.4 | 0.4 | 0.1 | 0.3 | 0.1 | 0.2 | 0.4 | 0.5 | 0.5 | 0.5 | | | | | | | | |
| 23-Jan-08 | 55 | 0.5 | 0.5 | 0.4 | 0.5 | 0.0 | 0.1 | 0.1 | 0.1 | 0.3 | 0.4 | 0.7 | 0.5 | | | | | | | | |
| 27-Jan-08 | 59 | 0.3 | 0.4 | 0.5 | 0.4 | 0.2 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.4 | 0.3 | | | | | | | | |

Table A.6 (Continued)

| Date | Days | Influent $NO_3$-N (mg/L) | | | | Effluent $NO_3$-N M-UASB (mg/L) | | | | Effluent $NO_3$-N T-UASB (mg/L) | | | | Effluent $NO_3$-N M-HUASB (mg/L) | | | | Effluent $NO_3$-N T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. |
| Low strength influent; HRT of three days (continued) | | | | | | | | | | | | | | | | | | | | | |
| 31-Jan-08 | 63 | 0.4 | 0.4 | 0.5 | 0.4 | 0.1 | 0.2 | 0.1 | 0.1 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.0 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 |
| 04-Feb-08 | 67 | 0.5 | 0.4 | 0.5 | 0.5 | 0.3 | 0.2 | 0.3 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 | 0.2 | 0.3 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| 10-Feb-08 | 73 | 0.5 | 0.5 | 0.4 | 0.5 | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.0 | 0.2 | 0.4 | 0.2 |
| 12-Feb-08 | 75 | 0.3 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | | | | | | | |
| 14-Feb-08 | 77 | 0.4 | 0.6 | 0.8 | 0.6 | 0.7 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.4 | 0.5 | 0.1 | 0.5 | 0.4 | 0.3 | 0.4 | 0.4 | 0.1 | 0.3 |
| 16-Feb-08 | 79 | 0.5 | 0.6 | 0.6 | 0.6 | 0.4 | 0.5 | 0.5 | 0.5 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.1 | 0.4 | 0.3 |
| 20-Feb-08 | 83 | 0.4 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.3 | 0.5 | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | 0.3 | 0.2 | 0.0 | 0.2 |
| 24-Feb-08 | 87 | 0.7 | 0.8 | 0.6 | 0.7 | 0.4 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 0.1 | 0.2 | 0.4 | 0.2 | 0.4 | 0.1 | 0.1 | 0.2 |
| 01-Mar-08 | 93 | 0.4 | 0.3 | 0.1 | 0.3 | 0.6 | 0.6 | 0.7 | 0.6 | 0.2 | 0.1 | 0.5 | 0.3 | 0.3 | 0.2 | 0.1 | 0.2 | 0.0 | 0.3 | 0.4 | 0.2 |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | | | | | | | |
| 09-Mar-08 | 101 | 0.5 | 0.4 | 0.3 | 0.4 | 0.5 | 0.3 | 0.2 | 0.3 | 0.2 | 0.4 | 0.4 | 0.3 | 0.5 | 0.6 | 0.4 | 0.5 | 0.4 | 0.7 | 0.8 | 0.6 |
| 13-Mar-08 | 105 | 0.5 | 0.6 | 0.6 | 0.6 | 0.1 | 0.2 | 0.4 | 0.2 | 0.5 | 0.4 | 0.3 | 0.4 | 0.6 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.5 | 0.5 |
| 17-Mar-08 | 109 | 0.6 | 0.7 | 0.5 | 0.6 | 0.4 | 0.4 | 0.1 | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 | 0.6 |
| 29-Mar-08 | 121 | 0.4 | 0.5 | 0.7 | 0.5 | 0.5 | 0.2 | 0.1 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.6 | 0.6 | 0.5 |
| 06-Apr-08 | 129 | 0.5 | 0.6 | 0.5 | 0.5 | 0.3 | 0.1 | 0.2 | 0.2 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.6 | 0.4 | 0.3 | 0.5 | 0.4 | 0.4 |
| 14-Apr-08 | 137 | 0.7 | 0.6 | 0.6 | 0.6 | 0.2 | 0.4 | 0.3 | 0.3 | 0.4 | 0.5 | 0.5 | 0.5 | 0.2 | 0.1 | 0.5 | 0.3 | 0.5 | 0.5 | 0.4 | 0.5 |
| 22-Apr-08 | 145 | 0.6 | 0.3 | 0.3 | 0.4 | 0.1 | 0.2 | 0.4 | 0.2 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.5 | 0.4 | 0.4 |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | | | | | | | |
| 29-Apr-08 | 152 | 0.2 | 0.3 | 0.3 | 0.3 | 0.1 | 0.0 | 0.2 | 0.1 | 0.2 | 0.3 | 0.4 | 0.3 | 0.3 | 0.2 | 0.1 | 0.2 | 0.5 | 0.3 | 0.4 | 0.4 |
| 05-May-08 | 158 | 0.3 | 0.5 | 0.4 | 0.4 | 0.0 | 0.3 | 0.4 | 0.2 | 0.4 | 0.4 | 0.5 | 0.4 | 0.3 | 0.2 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 |
| 09-May-08 | 162 | 0.7 | 0.5 | 0.3 | 0.5 | 0.1 | 0.2 | 0.3 | 0.2 | 0.2 | 0.5 | 0.6 | 0.4 | 0.3 | 0.2 | 0.1 | 0.2 | 0.2 | 0.3 | 0.1 | 0.2 |
| 15-May-08 | 168 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.2 | 0.3 | 0.6 | 0.4 | 0.3 | 0.4 | 0.3 | 0.2 | 0.2 | 0.2 | 0.4 | 0.3 | 0.3 | 0.3 |
| 17-May-08 | 170 | 0.4 | 0.5 | 0.4 | 0.4 | 0.0 | 0.3 | 0.4 | 0.2 | 0.4 | 0.5 | 0.7 | 0.5 | 0.2 | 0.3 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| 20-May-08 | 173 | 0.5 | 0.6 | 0.4 | 0.5 | 0.2 | 0.3 | 0.5 | 0.3 | 0.2 | 0.4 | 0.3 | 0.3 | 0.2 | 0.3 | 0.4 | 0.3 | 0.0 | 0.1 | 0.2 | 0.1 |
| 24-May-08 | 177 | 0.3 | 0.4 | 0.2 | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.5 | 0.5 | 0.2 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.2 | 0.3 | 0.1 | 0.2 |
| 26-May-08 | 179 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | 0.6 | 0.3 | 0.2 | 0.4 | 0.3 | 0.1 | 0.0 | 0.1 | 0.3 | 0.3 | 0.4 | 0.3 |

Table A.6 (Continued)

| Date | Days | Influent $NO_3$-N (mg/L) | | | | Effluent $NO_3$-N M-UASB (mg/L) | | | | Effluent $NO_3$-N T-UASB (mg/L) | | | | Effluent $NO_3$-N M-HUASB (mg/L) | | | | Effluent $NO_3$-N T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 0.3 | 0.2 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | 0.1 | 0.2 | 0.3 | 0.2 | 0.3 | 0.2 | 0.3 | 0.3 |
| 30-May-08 | 183 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.4 | 0.6 | 0.4 | 0.3 | 0.5 | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | 0.3 | 0.2 | 0.0 | 0.1 | 0.1 |
| 01-Jun-08 | 185 | 0.3 | 0.2 | 0.6 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.4 | 0.1 | 0.1 | 0.2 | 0.4 | 0.5 | 0.4 | 0.4 | 0.2 | 0.1 | 0.0 | 0.1 |
| 05-Jun-08 | 189 | 0.3 | 0.5 | 0.5 | 0.4 | 0.2 | 0.3 | 0.5 | 0.3 | 0.3 | 0.4 | 0.6 | 0.4 | 0.1 | 0.2 | 0.4 | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 |
| 07-Jun-08 | 191 | 0.5 | 0.5 | 0.6 | 0.5 | 0.1 | 0.2 | 0.4 | 0.2 | 0.4 | 0.2 | 0.5 | 0.4 | 0.2 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.1 | 0.2 |
| 09-Jun-08 | 193 | 0.7 | 0.6 | 0.5 | 0.6 | 0.2 | 0.3 | 0.1 | 0.2 | 0.1 | 0.5 | 0.4 | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 | 0.1 | 0.2 | 0.2 | 0.2 |
| 11-Jun-08 | 195 | 0.5 | 0.6 | 0.6 | 0.6 | 0.5 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.1 | 0.3 | 0.4 | 0.5 | 0.3 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 |
| 13-Jun-08 | 197 | 0.6 | 0.5 | 0.6 | 0.6 | 0.4 | 0.5 | 0.4 | 0.4 | 0.1 | 0.4 | 0.5 | 0.3 | 0.5 | 0.5 | 0.4 | 0.5 | 0.2 | 0.1 | 0.5 | 0.3 |
| 15-Jun-08 | 199 | 0.6 | 0.5 | 0.5 | 0.5 | 0.4 | 0.3 | 0.2 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.5 | 0.2 | 0.1 | 0.3 | 0.1 | 0.3 | 0.3 | 0.2 |

Table A.7 Influent and effluent TKN concentrations data in the UASB and HUASB reactors

| Date | Days | Titrant (mL) | Titrant (mL) | Sample (mL) | TKN (mg/L) | Titrant (mL) | TKN (mg/L) | Titrant (mL) | TKN (mg/L) | Titrant (mL) | TKN (mg/L) | Titrant (mL) | TKN (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Influent | Blank | | Influent | M-UASB | M-UASB | T-UASB | T-UASB | M-HUASB | M-HUASB | T-HUASB | T-HUASB |
| 08-Dec-07 | 9 | 21.773 | 1.853 | 150 | 37.2 | 18.836 | 31.7 | 20.007 | 33.9 | | | | |
| 12-Dec-07 | 13 | 20.592 | 0.984 | 150 | 36.6 | 19.659 | 34.9 | 19.868 | 35.3 | | | | |
| 22-Dec-07 | 23 | 20.318 | 1.312 | 150 | 35.5 | 18.237 | 31.6 | 18.864 | 32.8 | | | | |
| 03-Jan-08 | 35 | 19.971 | 1.117 | 150 | 35.2 | 18.783 | 33.0 | 18.579 | 32.6 | | | | |
| 17-Jan-08 | 49 | 20.787 | 0.897 | 150 | 37.1 | 19.157 | 34.1 | 19.850 | 35.4 | | | | |
| 31-Jan-08 | 63 | 21.296 | 1.223 | 150 | 37.5 | 19.232 | 33.6 | 20.113 | 35.3 | 18.263 | 31.8 | 19.497 | 34.1 |
| 20-Feb-08 | 83 | 32.321 | 2.840 | 150 | 55.0 | 28.655 | 48.2 | 28.880 | 48.6 | 26.214 | 43.6 | 28.470 | 47.8 |
| 01-Mar-08 | 93 | 30.152 | 0.924 | 150 | 54.6 | 28.334 | 51.2 | 29.768 | 53.8 | 27.397 | 49.4 | 28.345 | 51.2 |
| 17-Mar-08 | 109 | 30.677 | 0.887 | 150 | 55.6 | 26.388 | 47.6 | 29.122 | 52.7 | 27.753 | 50.1 | 29.235 | 52.9 |
| 06-Apr-08 | 129 | 31.879 | 0.972 | 150 | 57.7 | 32.896 | 59.6 | 29.957 | 54.1 | 28.520 | 51.4 | 29.672 | 53.6 |
| 22-Apr-08 | 145 | 31.351 | 0.845 | 150 | 56.9 | 31.231 | 56.7 | 30.481 | 55.3 | 28.863 | 52.3 | 30.294 | 55.0 |
| 09-May-08 | 162 | 29.431 | 1.126 | 150 | 52.8 | 25.852 | 46.2 | 27.337 | 48.9 | 26.832 | 48.0 | 27.492 | 49.2 |
| 17-May-08 | 170 | 28.451 | 1.223 | 150 | 50.8 | 25.187 | 44.7 | 26.472 | 47.1 | 25.539 | 45.4 | 25.963 | 46.2 |
| 24-May-08 | 177 | 28.364 | 1.149 | 150 | 50.8 | 25.944 | 46.3 | 27.747 | 49.6 | 26.354 | 47.0 | 26.881 | 48.0 |
| 05-Jun-08 | 189 | 27.974 | 1.173 | 150 | 50.0 | 26.749 | 47.7 | 26.948 | 48.1 | 26.539 | 47.3 | 26.554 | 47.4 |
| 13-Jun-08 | 197 | 27.738 | 1.281 | 150 | 49.4 | 26.783 | 47.6 | 26.977 | 48.0 | 26.142 | 46.4 | 26.459 | 47.0 |

Table A.8 Influent and effluent TP concentrations data in the UASB and HUASB reactors

| Date | Days | Influent TP (mg/L) | | | | Effluent TP M-UASB (mg/L) | | | | Effluent TP T-UASB (mg/L) | | | | Effluent TP M-HUASB (mg/L) | | | | Effluent TP T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. |
| Low strength influent; HRT of five days | | | | | | | | | | | | | | | | | | | | | |
| 02-Dec-07 | 3 | 4.5 | 4.7 | 5.3 | 4.8 | 18.6 | 17.5 | 18.8 | 18.3 | 11.3 | 10.6 | 11.2 | 11.0 | | | | | | | | |
| 04-Dec-07 | 5 | 6.6 | 6.1 | 6.9 | 6.5 | 17.4 | 17.2 | 17.6 | 17.4 | 18.5 | 18.7 | 18.9 | 18.7 | | | | | | | | |
| 08-Dec-07 | 9 | 6.9 | 7.7 | 7.5 | 7.4 | 16.6 | 16.4 | 15.9 | 16.3 | 20.1 | 20.2 | 21.3 | 20.5 | | | | | | | | |
| 10-Dec-07 | 11 | 6.8 | 7.5 | 7.6 | 7.3 | 17.9 | 16.8 | 16.6 | 17.1 | 24.6 | 22.8 | 25.8 | 24.4 | | | | | | | | |
| 12-Dec-07 | 13 | 6.8 | 7.5 | 7.1 | 7.1 | 17.1 | 17.5 | 17.3 | 17.3 | 22.4 | 23.8 | 28.3 | 24.8 | | | | | | | | |
| Low strength influent; HRT of three days | | | | | | | | | | | | | | | | | | | | | |
| 16-Dec-07 | 17 | 8.9 | 5.4 | 4.9 | 6.4 | 17.1 | 17.6 | 17.3 | 17.3 | 22.7 | 22.1 | 23.5 | 22.8 | | | | | | | | |
| 18-Dec-07 | 19 | 8.1 | 9.5 | 7.8 | 8.5 | 15.4 | 16.0 | 14.5 | 15.3 | 16.7 | 15.8 | 18.1 | 16.9 | | | | | | | | |
| 20-Dec-07 | 21 | 6.6 | 7.2 | 6.2 | 6.7 | 20.4 | 18.9 | 20.0 | 19.8 | 20.2 | 17.8 | 17.1 | 18.4 | | | | | | | | |
| 22-Dec-07 | 23 | 5.2 | 6.6 | 5.2 | 5.7 | 14.8 | 15.5 | 13.7 | 14.7 | 14.3 | 14.0 | 14.1 | 14.1 | | | | | | | | |
| 24-Dec-07 | 25 | 5.9 | 4.9 | 6.5 | 5.8 | 13.5 | 15.0 | 15.5 | 14.7 | 15.7 | 14.5 | 15.9 | 15.4 | | | | | | | | |
| 26-Dec-07 | 27 | 8.4 | 6.5 | 7.7 | 7.5 | 15.0 | 14.2 | 14.8 | 14.7 | 19.2 | 18.1 | 19.0 | 18.8 | | | | | | | | |
| 28-Dec-07 | 29 | 6.1 | 6.9 | 6.8 | 6.6 | 19.6 | 17.0 | 18.3 | 18.3 | 16.5 | 16.3 | 16.6 | 16.5 | | | | | | | | |
| 01-Jan-08 | 33 | 6.8 | 6.5 | 6.8 | 6.7 | 16.7 | 17.7 | 16.4 | 16.9 | 16.2 | 16.6 | 15.6 | 16.1 | | | | | | | | |
| 03-Jan-08 | 35 | 6.8 | 6.6 | 7.8 | 7.1 | 20.3 | 17.7 | 18.8 | 18.9 | 20.3 | 23.2 | 21.2 | 21.6 | | | | | | | | |
| 07-Jan-08 | 39 | 7.1 | 7.3 | 6.5 | 7.0 | 19.8 | 20.1 | 22.0 | 20.6 | 22.2 | 23.5 | 21.2 | 22.3 | | | | | | | | |
| 09-Jan-08 | 41 | 6.6 | 5.9 | 6.1 | 6.2 | 17.5 | 17.8 | 18.2 | 17.8 | 21.5 | 23.2 | 22.8 | 22.5 | | | | | | | | |
| 11-Jan-08 | 43 | 6.8 | 6.5 | 6.9 | 6.7 | 19.2 | 18.5 | 17.2 | 18.3 | 22.8 | 22.2 | 20.1 | 21.7 | | | | | | | | |
| 13-Jan-08 | 45 | 7.2 | 5.8 | 6.4 | 6.5 | 15.5 | 16.6 | 18.2 | 16.8 | 22.5 | 24.1 | 23.8 | 23.5 | | | | | | | | |
| 15-Jan-08 | 47 | 6.6 | 6.7 | 6.8 | 6.7 | 17.5 | 18.5 | 17.9 | 18.0 | 23.5 | 23.8 | 24.5 | 23.9 | | | | | | | | |
| 17-Jan-08 | 49 | 6.8 | 6.5 | 7.1 | 6.8 | 19.3 | 17.8 | 19.9 | 19.0 | 23.8 | 23.9 | 23.4 | 23.7 | | | | | | | | |

Table A.8 (Continued)

| Date | Days | Influent TP (mg/L) | | | | Effluent TP M-UASB (mg/L) | | | | Effluent TP T-UASB (mg/L) | | | | Effluent TP M-HUASB (mg/L) | | | | Effluent TP T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. |
| Low strength influent; HRT of three days (continued) | | | | | | | | | | | | | | | | | | | | | |
| 21-Jan-08 | 53 | 6.8 | 6.7 | 5.8 | 6.4 | 19.5 | 18.2 | 20.1 | 19.3 | 22.1 | 22.3 | 22.7 | 22.4 | | | | | | | | |
| 23-Jan-08 | 55 | 7.1 | 6.5 | 6.2 | 6.6 | 18.5 | 19.2 | 18.7 | 18.8 | 24.1 | 24.2 | 23.5 | 23.9 | | | | | | | | |
| 27-Jan-08 | 59 | 6.4 | 6.8 | 5.2 | 6.1 | 19.5 | 18.7 | 20.5 | 19.6 | 22.5 | 20.2 | 22.1 | 21.6 | | | | | | | | |
| 31-Jan-08 | 63 | 6.5 | 6.2 | 5.5 | 6.1 | 21.2 | 20.5 | 19.7 | 20.5 | 23.1 | 23.5 | 23.6 | 23.4 | 28.5 | 29.3 | 29.0 | 28.9 | 26.8 | 26.7 | 26.6 | 26.7 |
| 04-Feb-08 | 67 | 6.4 | 6.7 | 3.3 | 5.5 | 19.4 | 19.5 | 20.1 | 19.7 | 22.5 | 22.4 | 23.1 | 22.7 | 27.4 | 27.3 | 27.7 | 27.5 | 27.4 | 26.6 | 27.8 | 27.3 |
| 10-Feb-08 | 73 | 6.1 | 6.4 | 6.1 | 6.2 | 18.2 | 18.7 | 18.8 | 18.6 | 21.5 | 21.2 | 23.2 | 22.0 | 25.4 | 25.3 | 25.2 | 25.3 | 27.8 | 27.5 | 27.1 | 27.5 |
| 12-Feb-08 | 75 | 7.1 | 7.3 | 6.5 | 7.0 | 19.5 | 18.9 | 20.7 | 19.7 | 22.5 | 22.4 | 23.2 | 22.7 | 25.7 | 25.1 | 25.5 | 25.4 | 27.8 | 27.4 | 27.0 | 27.4 |
| High strength influent; HRT of five days | | | | | | | | | | | | | | | | | | | | | |
| 14-Feb-08 | 77 | 13.2 | 13.0 | 13.1 | 13.1 | 19.7 | 19.6 | 19.6 | 19.6 | 21.4 | 21.5 | 21.5 | 21.5 | 28.3 | 28.8 | 29.1 | 28.7 | 26.8 | 26.9 | 26.9 | 26.9 |
| 16-Feb-08 | 79 | 12.8 | 12.7 | 12.9 | 12.8 | 17.1 | 17.0 | 17.4 | 17.2 | 18.6 | 18.6 | 18.3 | 18.5 | 28.4 | 28.5 | 28.7 | 28.5 | 31.6 | 31.6 | 31.3 | 31.5 |
| 20-Feb-08 | 83 | 12.7 | 13.1 | 12.3 | 12.7 | 15.9 | 16.7 | 15.8 | 16.1 | 17.0 | 17.6 | 17.0 | 17.2 | 29.0 | 28.5 | 28.2 | 28.6 | 33.8 | 35.0 | 34.3 | 34.4 |
| 24-Feb-08 | 87 | 14.1 | 13.8 | 14.6 | 14.2 | 18.2 | 18.4 | 18.6 | 18.4 | 17.9 | 18.0 | 18.2 | 18.0 | 29.8 | 29.9 | 30.1 | 29.9 | 32.5 | 33.1 | 32.5 | 32.7 |
| 01-Mar-08 | 93 | 13.6 | 13.8 | 14.0 | 13.8 | 20.0 | 19.0 | 19.6 | 19.5 | 21.2 | 22.0 | 21.1 | 21.4 | 30.7 | 30.5 | 30.4 | 30.5 | 35.9 | 35.7 | 35.8 | 35.8 |
| High strength influent; HRT of four days | | | | | | | | | | | | | | | | | | | | | |
| 09-Mar-08 | 101 | 11.2 | 11.3 | 10.7 | 11.1 | 19.3 | 18.4 | 18.5 | 18.7 | 19.2 | 19.5 | 19.6 | 19.4 | 28.4 | 28.2 | 28.5 | 28.4 | 26.6 | 26.4 | 26.5 | 26.5 |
| 13-Mar-08 | 105 | 12.9 | 12.6 | 12.2 | 12.6 | 18.5 | 18.8 | 18.9 | 18.7 | 20.8 | 21.2 | 20.4 | 20.8 | 25.7 | 25.5 | 25.3 | 25.5 | 27.9 | 27.7 | 27.2 | 27.6 |
| 17-Mar-08 | 109 | 10.9 | 11.2 | 10.6 | 10.9 | 13.9 | 15.1 | 14.4 | 14.5 | 16.5 | 16.7 | 16.9 | 16.7 | 22.1 | 21.7 | 21.3 | 21.7 | 27.3 | 26.7 | 27.5 | 27.2 |
| 29-Mar-08 | 121 | 12.0 | 12.1 | 12.1 | 12.1 | 32.6 | 31.8 | 33.0 | 32.5 | 16.6 | 16.3 | 16.3 | 16.4 | 22.7 | 22.6 | 22.8 | 22.7 | 25.6 | 26.1 | 25.7 | 25.8 |
| 06-Apr-08 | 129 | 11.8 | 11.8 | 11.5 | 11.7 | 27.6 | 27.4 | 27.5 | 27.5 | 19.7 | 19.4 | 19.4 | 19.5 | 23.2 | 23.6 | 22.9 | 23.2 | 28.4 | 28.5 | 28.7 | 28.5 |
| 14-Apr-08 | 137 | 10.2 | 10.6 | 10.5 | 10.4 | 22.2 | 22.3 | 22.7 | 22.4 | 17.7 | 17.7 | 17.6 | 17.6 | 21.8 | 21.6 | 21.5 | 21.6 | 24.9 | 24.1 | 24.6 | 24.5 |
| 22-Apr-08 | 145 | 10.7 | 10.7 | 10.6 | 10.7 | 20.9 | 20.4 | 20.1 | 20.5 | 18.5 | 19.3 | 19.0 | 19.0 | 19.3 | 19.0 | 19.8 | 19.3 | 26.6 | 26.9 | 27.0 | 26.8 |

Table A.8 (Continued)

| Date | Days | Influent TP (mg/L) | | | | Effluent TP M-UASB (mg/L) | | | | Effluent TP T-UASB (mg/L) | | | | Effluent TP M-HUASB (mg/L) | | | | Effluent TP T-HUASB (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. | S1 | S2 | S3 | Ave. |
| High strength influent; HRT of three days | | | | | | | | | | | | | | | | | | | | | |
| 29-Apr-08 | 152 | 11.0 | 11.3 | 11.4 | 11.2 | 18.1 | 18.0 | 18.4 | 18.2 | 15.3 | 15.4 | 15.6 | 15.4 | 22.5 | 21.5 | 22.1 | 22.0 | 27.1 | 27.6 | 27.2 | 27.3 |
| 05-May-08 | 158 | 12.1 | 12.9 | 12.6 | 12.5 | 14.7 | 14.5 | 14.3 | 14.5 | 16.0 | 15.8 | 16.3 | 16.1 | 24.8 | 24.9 | 25.1 | 24.9 | 28.2 | 28.7 | 29.0 | 28.6 |
| 09-May-08 | 162 | 11.9 | 12.4 | 12.0 | 12.1 | 14.9 | 14.8 | 14.6 | 14.8 | 19.1 | 18.9 | 19.0 | 19.0 | 24.0 | 24.3 | 23.7 | 24.0 | 27.3 | 27.0 | 26.9 | 27.1 |
| 15-May-08 | 168 | 10.9 | 10.8 | 10.6 | 10.8 | 14.3 | 13.7 | 14.5 | 14.2 | 17.4 | 16.6 | 17.8 | 17.2 | 23.6 | 23.7 | 23.9 | 23.7 | 29.6 | 29.7 | 29.9 | 29.7 |
| 17-May-08 | 170 | 11.1 | 10.9 | 11.2 | 11.1 | 14.1 | 13.8 | 14.6 | 14.2 | 18.3 | 18.9 | 18.3 | 18.5 | 22.8 | 22.9 | 22.3 | 22.7 | 27.6 | 27.4 | 27.5 | 27.5 |
| 20-May-08 | 173 | 12.5 | 12.3 | 12.2 | 12.3 | 14.3 | 13.3 | 13.9 | 13.8 | 18.8 | 18.4 | 18.0 | 18.4 | 21.6 | 21.9 | 22.0 | 21.8 | 26.7 | 26.1 | 26.5 | 26.4 |
| 24-May-08 | 177 | 11.6 | 11.7 | 12.1 | 11.8 | 15.6 | 15.7 | 15.1 | 15.5 | 18.3 | 18.1 | 17.6 | 18.0 | 22.2 | 22.6 | 21.8 | 22.2 | 26.9 | 26.1 | 26.6 | 26.5 |
| 26-May-08 | 179 | 11.3 | 12.1 | 11.2 | 11.5 | 15.4 | 15.2 | 14.7 | 15.1 | 18.7 | 18.5 | 19.0 | 18.7 | 23.3 | 23.6 | 23.7 | 23.5 | 25.7 | 25.8 | 26.0 | 25.8 |
| High strength influent; HRT of two days | | | | | | | | | | | | | | | | | | | | | |
| 28-May-08 | 181 | 11.6 | 12.0 | 11.3 | 11.6 | 14.8 | 14.7 | 14.9 | 14.8 | 18.6 | 18.7 | 18.6 | 18.6 | 24.1 | 23.3 | 23.8 | 23.7 | 25.6 | 25.5 | 25.4 | 25.5 |
| 30-May-08 | 183 | 12.5 | 12.2 | 11.8 | 12.2 | 14.9 | 14.7 | 14.6 | 14.7 | 18.3 | 18.4 | 18.6 | 18.4 | 24.6 | 24.7 | 25.1 | 24.8 | 25.3 | 25.4 | 25.6 | 25.4 |
| 01-Jun-08 | 185 | 11.4 | 12.6 | 11.9 | 12.0 | 13.8 | 13.2 | 13.6 | 13.5 | 18.5 | 18.0 | 17.7 | 18.1 | 26.3 | 25.5 | 26.0 | 25.9 | 25.5 | 25.6 | 25.8 | 25.6 |
| 05-Jun-08 | 189 | 10.8 | 10.9 | 11.1 | 10.9 | 13.2 | 13.3 | 13.2 | 13.2 | 18.0 | 17.7 | 17.6 | 17.8 | 22.5 | 22.9 | 22.2 | 22.5 | 26.3 | 26.6 | 26.0 | 26.3 |
| 07-Jun-08 | 191 | 11.4 | 11.2 | 11.3 | 11.3 | 12.8 | 12.7 | 12.6 | 12.7 | 18.1 | 17.5 | 18.3 | 18.0 | 23.1 | 22.9 | 23.2 | 23.1 | 26.8 | 26.8 | 26.7 | 26.8 |
| 09-Jun-08 | 193 | 11.2 | 11.5 | 11.6 | 11.4 | 12.7 | 12.8 | 13.0 | 12.8 | 17.7 | 17.5 | 17.3 | 17.5 | 23.6 | 22.7 | 22.8 | 23.0 | 26.8 | 26.7 | 26.7 | 26.7 |
| 11-Jun-08 | 195 | 11.4 | 11.3 | 11.5 | 11.4 | 12.7 | 13.2 | 13.5 | 13.1 | 17.4 | 17.3 | 17.1 | 17.3 | 24.4 | 24.7 | 24.1 | 24.4 | 27.1 | 26.9 | 27.4 | 27.1 |
| 13-Jun-08 | 197 | 12.1 | 11.9 | 12.4 | 12.1 | 12.8 | 13.2 | 13.1 | 13.0 | 17.6 | 17.3 | 17.2 | 17.4 | 23.9 | 23.6 | 23.6 | 23.7 | 27.4 | 27.2 | 27.3 | 27.3 |
| 15-Jun-08 | 199 | 11.3 | 11.7 | 11.6 | 11.5 | 12.7 | 12.7 | 12.6 | 12.7 | 18.7 | 17.8 | 17.9 | 18.1 | 23.9 | 23.8 | 23.7 | 23.8 | 27.1 | 26.3 | 27.5 | 27.0 |

# APPENDIX B
# STATISTICAL ANALYSIS

One-way ANOVA for COD concentration

This table provides a comparison of means for each operation of condition against each other operation condition. The important aspect to this table is a Sig. column that provides the exact significance for the difference between any two means, where this is less than 0.05, SPSS places a * symbol next to the value in the Mean Difference column, it is indicating a significant difference of the two samples being compared at significance level of 0.05.

Table B.1 One-way ANOVA Multiple Comparisons with COD removal as dependent variable (Tukey HSD Method)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MUASB;5 day-low | MUASB;3 day-low | .7074 | .93923 | 1.000 | -2.7139 | 4.1286 |
| | MUASB;5 day-high | -4.7745(*) | 1.14156 | .008 | -8.9327 | -.6162 |
| | MUASB;4 day-high | .8114 | 1.17900 | 1.000 | -3.4832 | 5.1061 |
| | MUASB;3 day-high | 7.6988(*) | 1.06645 | .000 | 3.8142 | 11.5835 |
| | MUASB;2 day-high | 13.5754(*) | 1.11157 | .000 | 9.5264 | 17.6244 |
| | TUASB;5 day-low | 7.3718(*) | 1.38250 | .000 | 2.3359 | 12.4077 |
| | TUASB;3 day-low | 4.2043(*) | .99056 | .006 | .5961 | 7.8125 |
| | TUASB;5 day-high | -2.1545 | 1.14156 | .956 | -6.3127 | 2.0038 |
| | TUASB;4 day-high | 4.2764(*) | 1.02105 | .008 | .5571 | 7.9957 |
| | TUASB;3 day-high | 12.7432(*) | 1.11157 | .000 | 8.6941 | 16.7922 |
| | TUASB;2 day-high | 19.7793(*) | 1.22715 | .000 | 15.3093 | 24.2493 |
| | MHUASB;3 day-low | -.3740 | 1.22715 | 1.000 | -4.8441 | 4.0960 |
| | MTUASB;5 day-high | -5.9895(*) | 1.14156 | .000 | -10.1477 | -1.8312 |
| | MHUASB;4 day-high | -1.7936 | 1.02105 | .979 | -5.5129 | 1.9257 |
| | MHUASB;3 day-high | 2.1929 | 1.02105 | .862 | -1.5264 | 5.9121 |
| | MHUASB;2 day-high | 5.2633(*) | 1.08699 | .001 | 1.3038 | 9.2228 |
| | THUASB;3 day-low | 21.7818(*) | 1.38250 | .000 | 16.7459 | 26.8177 |
| | THUASB;5 day-high | .9955 | 1.14156 | 1.000 | -3.1627 | 5.1538 |
| | THUASB;4 day-high | 6.1901(*) | 1.04903 | .000 | 2.3689 | 10.0113 |
| | THUASB;3 day-high | 8.2785(*) | 1.04903 | .000 | 4.4573 | 12.0997 |
| | THUASB;2 day-high | 13.7143(*) | 1.08699 | .000 | 9.7548 | 17.6738 |

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

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MUASB;3 day-low | MUASB;5 day-low | -.7074 | .93923 | 1.000 | -4.1286 | 2.7139 |
| | MUASB;5 day-high | -5.4818(*) | .89178 | .000 | -8.7302 | -2.2334 |
| | MUASB;4 day-high | .1041 | .93923 | 1.000 | -3.3172 | 3.5253 |
| | MUASB;3 day-high | 6.9915(*) | .79335 | .000 | 4.1016 | 9.8814 |
| | MUASB;2 day-high | 12.8680(*) | .85305 | .000 | 9.7607 | 15.9754 |
| | TUASB;5 day-low | 6.6644(*) | 1.18466 | .000 | 2.3492 | 10.9797 |
| | TUASB;3 day-low | 3.4969(*) | .68797 | .000 | .9909 | 6.0029 |
| | TUASB;5 day-high | -2.8618 | .89178 | .169 | -6.1102 | .3866 |
| | TUASB;4 day-high | 3.5691(*) | .73119 | .000 | .9056 | 6.2325 |
| | TUASB;3 day-high | 12.0358(*) | .85305 | .000 | 8.9285 | 15.1431 |
| | TUASB;2 day-high | 19.0719(*) | .99899 | .000 | 15.4330 | 22.7109 |
| | MHUASB;3 day-low | -1.0814 | .99899 | 1.000 | -4.7204 | 2.5575 |
| | MTUASB;5 day-high | -6.6968(*) | .89178 | .000 | -9.9452 | -3.4484 |
| | MHUASB;4 day-high | -2.5009 | .73119 | .097 | -5.1644 | .1625 |
| | MHUASB;3 day-high | 1.4855 | .73119 | .913 | -1.1779 | 4.1489 |
| | MHUASB;2 day-high | 4.5559(*) | .82075 | .000 | 1.5662 | 7.5456 |
| | THUASB;3 day-low | 21.0744(*) | 1.18466 | .000 | 16.7592 | 25.3897 |
| | THUASB;5 day-high | .2882 | .89178 | 1.000 | -2.9602 | 3.5366 |
| | THUASB;4 day-high | 5.4828(*) | .76977 | .000 | 2.6788 | 8.2867 |
| | THUASB;3 day-high | 7.5711(*) | .76977 | .000 | 4.7671 | 10.3751 |
| | THUASB;2 day-high | 13.0069(*) | .82075 | .000 | 10.0172 | 15.9966 |
| MUASB;5 day-high | MUASB;5 day-low | 4.7745(*) | 1.14156 | .008 | .6162 | 8.9327 |
| | MUASB;3 day-low | 5.4818(*) | .89178 | .000 | 2.2334 | 8.7302 |
| | MUASB;4 day-high | 5.5859(*) | 1.14156 | .000 | 1.4276 | 9.7442 |
| | MUASB;3 day-high | 12.4733(*) | 1.02491 | .000 | 8.7400 | 16.2066 |
| | MUASB;2 day-high | 18.3499(*) | 1.07178 | .000 | 14.4458 | 22.2540 |
| | TUASB;5 day-low | 12.1462(*) | 1.35072 | .000 | 7.2261 | 17.0664 |
| | TUASB;3 day-low | 8.9787(*) | .94569 | .000 | 5.5340 | 12.4235 |
| | TUASB;5 day-high | 2.6200 | 1.10286 | .724 | -1.3973 | 6.6373 |
| | TUASB;4 day-high | 9.0509(*) | .97758 | .000 | 5.4900 | 12.6118 |
| | TUASB;3 day-high | 17.5176(*) | 1.07178 | .000 | 13.6135 | 21.4217 |
| | TUASB;2 day-high | 24.5537(*) | 1.19122 | .000 | 20.2146 | 28.8929 |
| | MHUASB;3 day-low | 4.4004(*) | 1.19122 | .043 | .0613 | 8.7396 |
| | MTUASB;5 day-high | -1.2150 | 1.10286 | 1.000 | -5.2323 | 2.8023 |
| | MHUASB;4 day-high | 2.9809 | .97758 | .246 | -.5800 | 6.5418 |
| | MHUASB;3 day-high | 6.9673(*) | .97758 | .000 | 3.4064 | 10.5283 |
| | MHUASB;2 day-high | 10.0377(*) | 1.04626 | .000 | 6.2266 | 13.8489 |
| | THUASB;3 day-low | 26.5562(*) | 1.35072 | .000 | 21.6361 | 31.4764 |
| | THUASB;5 day-high | 5.7700(*) | 1.10286 | .000 | 1.7527 | 9.7873 |
| | THUASB;4 day-high | 10.9646(*) | 1.00677 | .000 | 7.2973 | 14.6318 |
| | THUASB;3 day-high | 13.0529(*) | 1.00677 | .000 | 9.3857 | 16.7202 |
| | THUASB;2 day-high | 18.4887(*) | 1.04626 | .000 | 14.6776 | 22.2999 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MUASB;4 day-high | MUASB;5 day-low | -.8114 | 1.17900 | 1.000 | -5.1061 | 3.4832 |
| | MUASB;3 day-low | -.1041 | .93923 | 1.000 | -3.5253 | 3.3172 |
| | MUASB;5 day-high | -5.5859(*) | 1.14156 | .000 | -9.7442 | -1.4276 |
| | MUASB;3 day-high | 6.8874(*) | 1.06645 | .000 | 3.0027 | 10.7721 |
| | MUASB;2 day-high | 12.7640(*) | 1.11157 | .000 | 8.7149 | 16.8130 |
| | TUASB;5 day-low | 6.5604(*) | 1.38250 | .001 | 1.5244 | 11.5963 |
| | TUASB;3 day-low | 3.3929 | .99056 | .095 | -.2154 | 7.0011 |
| | TUASB;5 day-high | -2.9659 | 1.14156 | .557 | -7.1242 | 1.1924 |
| | TUASB;4 day-high | 3.4650 | 1.02105 | .104 | -.2543 | 7.1843 |
| | TUASB;3 day-high | 11.9317(*) | 1.11157 | .000 | 7.8827 | 15.9808 |
| | TUASB;2 day-high | 18.9679(*) | 1.22715 | .000 | 14.4978 | 23.4379 |
| | MHUASB;3 day-low | -1.1855 | 1.22715 | 1.000 | -5.6555 | 3.2845 |
| | MTUASB;5 day-high | -6.8009(*) | 1.14156 | .000 | -10.9592 | -2.6426 |
| | MHUASB;4 day-high | -2.6050 | 1.02105 | .593 | -6.3243 | 1.1143 |
| | MHUASB;3 day-high | 1.3814 | 1.02105 | .999 | -2.3379 | 5.1007 |
| | MHUASB;2 day-high | 4.4519(*) | 1.08699 | .011 | .4924 | 8.4113 |
| | THUASB;3 day-low | 20.9704(*) | 1.38250 | .000 | 15.9344 | 26.0063 |
| | THUASB;5 day-high | .1841 | 1.14156 | 1.000 | -3.9742 | 4.3424 |
| | THUASB;4 day-high | 5.3787(*) | 1.04903 | .000 | 1.5575 | 9.1999 |
| | THUASB;3 day-high | 7.4670(*) | 1.04903 | .000 | 3.6458 | 11.2882 |
| | THUASB;2 day-high | 12.9029(*) | 1.08699 | .000 | 8.9434 | 16.8623 |
| MUASB;3 day-high | MUASB;5 day-low | -7.6988(*) | 1.06645 | .000 | -11.5835 | -3.8142 |
| | MUASB;3 day-low | -6.9915(*) | .79335 | .000 | -9.8814 | -4.1016 |
| | MUASB;5 day-high | -12.4733(*) | 1.02491 | .000 | -16.2066 | -8.7400 |
| | MUASB;4 day-high | -6.8874(*) | 1.06645 | .000 | -10.7721 | -3.0027 |
| | MUASB;2 day-high | 5.8766(*) | .99139 | .000 | 2.2653 | 9.4878 |
| | TUASB;5 day-low | -.3270 | 1.28786 | 1.000 | -5.0182 | 4.3641 |
| | TUASB;3 day-low | -3.4945(*) | .85351 | .011 | -6.6035 | -.3855 |
| | TUASB;5 day-high | -9.8533(*) | 1.02491 | .000 | -13.5866 | -6.1200 |
| | TUASB;4 day-high | -3.4224(*) | .88871 | .025 | -6.6596 | -.1852 |
| | TUASB;3 day-high | 5.0443(*) | .99139 | .000 | 1.4331 | 8.6556 |
| | TUASB;2 day-high | 12.0805(*) | 1.11944 | .000 | 8.0028 | 16.1582 |
| | MHUASB;3 day-low | -8.0729(*) | 1.11944 | .000 | -12.1506 | -3.9952 |
| | MTUASB;5 day-high | -13.6883(*) | 1.02491 | .000 | -17.4216 | -9.9550 |
| | MHUASB;4 day-high | -9.4924(*) | .88871 | .000 | -12.7296 | -6.2552 |
| | MHUASB;3 day-high | -5.5060(*) | .88871 | .000 | -8.7432 | -2.2688 |
| | MHUASB;2 day-high | -2.4355 | .96375 | .612 | -5.9461 | 1.0750 |
| | THUASB;3 day-low | 14.0830(*) | 1.28786 | .000 | 9.3918 | 18.7741 |
| | THUASB;5 day-high | -6.7033(*) | 1.02491 | .000 | -10.4366 | -2.9700 |
| | THUASB;4 day-high | -1.5087 | .92072 | .991 | -4.8625 | 1.8451 |
| | THUASB;3 day-high | .5796 | .92072 | 1.000 | -2.7742 | 3.9334 |
| | THUASB;2 day-high | 6.0155(*) | .96375 | .000 | 2.5049 | 9.5260 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MUASB;2 day-high | MUASB;5 day-low | -13.5754(*) | 1.11157 | .000 | -17.6244 | -9.5264 |
| | MUASB;3 day-low | -12.8680(*) | .85305 | .000 | -15.9754 | -9.7607 |
| | MUASB;5 day-high | -18.3499(*) | 1.07178 | .000 | -22.2540 | -14.4458 |
| | MUASB;4 day-high | -12.7640(*) | 1.11157 | .000 | -16.8130 | -8.7149 |
| | MUASB;3 day-high | -5.8766(*) | .99139 | .000 | -9.4878 | -2.2653 |
| | TUASB;5 day-low | -6.2036(*) | 1.32547 | .001 | -11.0318 | -1.3754 |
| | TUASB;3 day-low | -9.3711(*) | .90926 | .000 | -12.6832 | -6.0590 |
| | TUASB;5 day-high | -15.7299(*) | 1.07178 | .000 | -19.6340 | -11.8258 |
| | TUASB;4 day-high | -9.2990(*) | .94238 | .000 | -12.7317 | -5.8662 |
| | TUASB;3 day-high | -.8322 | 1.03978 | 1.000 | -4.6198 | 2.9553 |
| | TUASB;2 day-high | 6.2039(*) | 1.16251 | .000 | 1.9693 | 10.4385 |
| | MHUASB;3 day-low | -13.9494(*) | 1.16251 | .000 | -18.1840 | -9.7149 |
| | MTUASB;5 day-high | -19.5649(*) | 1.07178 | .000 | -23.4690 | -15.6608 |
| | MHUASB;4 day-high | -15.3690(*) | .94238 | .000 | -18.8017 | -11.9362 |
| | MHUASB;3 day-high | -11.3825(*) | .94238 | .000 | -14.8153 | -7.9498 |
| | MHUASB;2 day-high | -8.3121(*) | 1.01346 | .000 | -12.0037 | -4.6205 |
| | THUASB;3 day-low | 8.2064(*) | 1.32547 | .000 | 3.3782 | 13.0346 |
| | THUASB;5 day-high | -12.5799(*) | 1.07178 | .000 | -16.4840 | -8.6758 |
| | THUASB;4 day-high | -7.3853(*) | .97263 | .000 | -10.9282 | -3.8424 |
| | THUASB;3 day-high | -5.2969(*) | .97263 | .000 | -8.8399 | -1.7540 |
| | THUASB;2 day-high | .1389 | 1.01346 | 1.000 | -3.5527 | 3.8305 |
| TUASB;5 day-low | MUASB;5 day-low | -7.3718(*) | 1.38250 | .000 | -12.4077 | -2.3359 |
| | MUASB;3 day-low | -6.6644(*) | 1.18466 | .000 | -10.9797 | -2.3492 |
| | MUASB;5 day-high | -12.1462(*) | 1.35072 | .000 | -17.0664 | -7.2261 |
| | MUASB;4 day-high | -6.5604(*) | 1.38250 | .001 | -11.5963 | -1.5244 |
| | MUASB;3 day-high | .3270 | 1.28786 | 1.000 | -4.3641 | 5.0182 |
| | MUASB;2 day-high | 6.2036(*) | 1.32547 | .001 | 1.3754 | 11.0318 |
| | TUASB;3 day-low | -3.1675 | 1.22576 | .568 | -7.6325 | 1.2975 |
| | TUASB;5 day-high | -9.5263(*) | 1.35072 | .000 | -14.4464 | -4.6061 |
| | TUASB;4 day-high | -3.0954 | 1.25052 | .651 | -7.6505 | 1.4598 |
| | TUASB;3 day-high | 5.3714(*) | 1.32547 | .013 | .5432 | 10.1996 |
| | TUASB;2 day-high | 12.4075(*) | 1.42378 | .000 | 7.2212 | 17.5938 |
| | MHUASB;3 day-low | -7.7458(*) | 1.42378 | .000 | -12.9321 | -2.5595 |
| | MTUASB;5 day-high | -13.3613(*) | 1.35072 | .000 | -18.2814 | -8.4411 |
| | MHUASB;4 day-high | -9.1654(*) | 1.25052 | .000 | -13.7205 | -4.6102 |
| | MHUASB;3 day-high | -5.1789(*) | 1.25052 | .009 | -9.7341 | -.6238 |
| | MHUASB;2 day-high | -2.1085 | 1.30492 | .992 | -6.8618 | 2.6448 |
| | THUASB;3 day-low | 14.4100(*) | 1.55967 | .000 | 8.7287 | 20.0913 |
| | THUASB;5 day-high | -6.3763(*) | 1.35072 | .001 | -11.2964 | -1.4561 |
| | THUASB;4 day-high | -1.1817 | 1.27347 | 1.000 | -5.8204 | 3.4571 |
| | THUASB;3 day-high | .9067 | 1.27347 | 1.000 | -3.7321 | 5.5454 |
| | THUASB;2 day-high | 6.3425(*) | 1.30492 | .000 | 1.5892 | 11.0958 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| TUASB;3 day-low | MUASB;5 day-low | -4.2043(*) | .99056 | .006 | -7.8125 | -.5961 |
| | MUASB;3 day-low | -3.4969(*) | .68797 | .000 | -6.0029 | -.9909 |
| | MUASB;5 day-high | -8.9787(*) | .94569 | .000 | -12.4235 | -5.5340 |
| | MUASB;4 day-high | -3.3929 | .99056 | .095 | -7.0011 | .2154 |
| | MUASB;3 day-high | 3.4945(*) | .85351 | .011 | .3855 | 6.6035 |
| | MUASB;2 day-high | 9.3711(*) | .90926 | .000 | 6.0590 | 12.6832 |
| | TUASB;5 day-low | 3.1675 | 1.22576 | .568 | -1.2975 | 7.6325 |
| | TUASB;5 day-high | -6.3588(*) | .94569 | .000 | -9.8035 | -2.9140 |
| | TUASB;4 day-high | .0721 | .79605 | 1.000 | -2.8276 | 2.9719 |
| | TUASB;3 day-high | 8.5389(*) | .90926 | .000 | 5.2268 | 11.8510 |
| | TUASB;2 day-high | 15.5750(*) | 1.04740 | .000 | 11.7597 | 19.3903 |
| | MHUASB;3 day-low | -4.5783(*) | 1.04740 | .004 | -8.3936 | -.7631 |
| | MTUASB;5 day-high | -10.1938(*) | .94569 | .000 | -13.6385 | -6.7490 |
| | MHUASB;4 day-high | -5.9979(*) | .79605 | .000 | -8.8976 | -3.0981 |
| | MHUASB;3 day-high | -2.0114 | .79605 | .612 | -4.9111 | .8883 |
| | MHUASB;2 day-high | 1.0590 | .87904 | 1.000 | -2.1430 | 4.2610 |
| | THUASB;3 day-low | 17.5775(*) | 1.22576 | .000 | 13.1125 | 22.0425 |
| | THUASB;5 day-high | -3.2088 | .94569 | .104 | -6.6535 | .2360 |
| | THUASB;4 day-high | 1.9858 | .83164 | .715 | -1.0435 | 5.0152 |
| | THUASB;3 day-high | 4.0742(*) | .83164 | .000 | 1.0448 | 7.1035 |
| | THUASB;2 day-high | 9.5100(*) | .87904 | .000 | 6.3080 | 12.7120 |
| TUASB;5 day-high | MUASB;5 day-low | 2.1545 | 1.14156 | .956 | -2.0038 | 6.3127 |
| | MUASB;3 day-low | 2.8618 | .89178 | .169 | -.3866 | 6.1102 |
| | MUASB;5 day-high | -2.6200 | 1.10286 | .724 | -6.6373 | 1.3973 |
| | MUASB;4 day-high | 2.9659 | 1.14156 | .557 | -1.1924 | 7.1242 |
| | MUASB;3 day-high | 9.8533(*) | 1.02491 | .000 | 6.1200 | 13.5866 |
| | MUASB;2 day-high | 15.7299(*) | 1.07178 | .000 | 11.8258 | 19.6340 |
| | TUASB;5 day-low | 9.5263(*) | 1.35072 | .000 | 4.6061 | 14.4464 |
| | TUASB;3 day-low | 6.3588(*) | .94569 | .000 | 2.9140 | 9.8035 |
| | TUASB;4 day-high | 6.4309(*) | .97758 | .000 | 2.8700 | 9.9918 |
| | TUASB;3 day-high | 14.8976(*) | 1.07178 | .000 | 10.9935 | 18.8017 |
| | TUASB;2 day-high | 21.9338(*) | 1.19122 | .000 | 17.5946 | 26.2729 |
| | MHUASB;3 day-low | 1.7804 | 1.19122 | .997 | -2.5587 | 6.1196 |
| | MTUASB;5 day-high | -3.8350 | 1.10286 | .082 | -7.8523 | .1823 |
| | MHUASB;4 day-high | .3609 | .97758 | 1.000 | -3.2000 | 3.9218 |
| | MHUASB;3 day-high | 4.3473(*) | .97758 | .003 | .7864 | 7.9083 |
| | MHUASB;2 day-high | 7.4178(*) | 1.04626 | .000 | 3.6066 | 11.2289 |
| | THUASB;3 day-low | 23.9363(*) | 1.35072 | .000 | 19.0161 | 28.8564 |
| | THUASB;5 day-high | 3.1500 | 1.10286 | .365 | -.8673 | 7.1673 |
| | THUASB;4 day-high | 8.3446(*) | 1.00677 | .000 | 4.6773 | 12.0118 |
| | THUASB;3 day-high | 10.4329(*) | 1.00677 | .000 | 6.7657 | 14.1002 |
| | THUASB;2 day-high | 15.8688(*) | 1.04626 | .000 | 12.0576 | 19.6799 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| TUASB;4 day-high | MUASB;5 day-low | -4.2764(*) | 1.02105 | .008 | -7.9957 | -.5571 |
| | MUASB;3 day-low | -3.5691(*) | .73119 | .000 | -6.2325 | -.9056 |
| | MUASB;5 day-high | -9.0509(*) | .97758 | .000 | -12.6118 | -5.4900 |
| | MUASB;4 day-high | -3.4650 | 1.02105 | .104 | -7.1843 | .2543 |
| | MUASB;3 day-high | 3.4224(*) | .88871 | .025 | .1852 | 6.6596 |
| | MUASB;2 day-high | 9.2990(*) | .94238 | .000 | 5.8662 | 12.7317 |
| | TUASB;5 day-low | 3.0954 | 1.25052 | .651 | -1.4598 | 7.6505 |
| | TUASB;3 day-low | -.0721 | .79605 | 1.000 | -2.9719 | 2.8276 |
| | TUASB;5 day-high | -6.4309(*) | .97758 | .000 | -9.9918 | -2.8700 |
| | TUASB;3 day-high | 8.4667(*) | .94238 | .000 | 5.0340 | 11.8995 |
| | TUASB;2 day-high | 15.5029(*) | 1.07628 | .000 | 11.5824 | 19.4233 |
| | MHUASB;3 day-low | -4.6505(*) | 1.07628 | .005 | -8.5709 | -.7300 |
| | MTUASB;5 day-high | -10.2659(*) | .97758 | .000 | -13.8268 | -6.7050 |
| | MHUASB;4 day-high | -6.0700(*) | .83368 | .000 | -9.1068 | -3.0332 |
| | MHUASB;3 day-high | -2.0836 | .83368 | .633 | -5.1204 | .9532 |
| | MHUASB;2 day-high | .9869 | .91325 | 1.000 | -2.3398 | 4.3135 |
| | THUASB;3 day-low | 17.5054(*) | 1.25052 | .000 | 12.9502 | 22.0605 |
| | THUASB;5 day-high | -3.2809 | .97758 | .115 | -6.8418 | .2800 |
| | THUASB;4 day-high | 1.9137 | .86772 | .832 | -1.2471 | 5.0745 |
| | THUASB;3 day-high | 4.0020(*) | .86772 | .001 | .8412 | 7.1628 |
| | THUASB;2 day-high | 9.4379(*) | .91325 | .000 | 6.1112 | 12.7645 |
| TUASB;3 day-high | MUASB;5 day-low | -12.7432(*) | 1.11157 | .000 | -16.7922 | -8.6941 |
| | MUASB;3 day-low | -12.0358(*) | .85305 | .000 | -15.1431 | -8.9285 |
| | MUASB;5 day-high | -17.5176(*) | 1.07178 | .000 | -21.4217 | -13.6135 |
| | MUASB;4 day-high | -11.9317(*) | 1.11157 | .000 | -15.9808 | -7.8827 |
| | MUASB;3 day-high | -5.0443(*) | .99139 | .000 | -8.6556 | -1.4331 |
| | MUASB;2 day-high | .8322 | 1.03978 | 1.000 | -2.9553 | 4.6198 |
| | TUASB;5 day-low | -5.3714(*) | 1.32547 | .013 | -10.1996 | -.5432 |
| | TUASB;3 day-low | -8.5389(*) | .90926 | .000 | -11.8510 | -5.2268 |
| | TUASB;5 day-high | -14.8976(*) | 1.07178 | .000 | -18.8017 | -10.9935 |
| | TUASB;4 day-high | -8.4667(*) | .94238 | .000 | -11.8995 | -5.0340 |
| | TUASB;2 day-high | 7.0361(*) | 1.16251 | .000 | 2.8015 | 11.2707 |
| | MHUASB;3 day-low | -13.1172(*) | 1.16251 | .000 | -17.3518 | -8.8826 |
| | MTUASB;5 day-high | -18.7326(*) | 1.07178 | .000 | -22.6367 | -14.8285 |
| | MHUASB;4 day-high | -14.5367(*) | .94238 | .000 | -17.9695 | -11.1040 |
| | MHUASB;3 day-high | -10.5503(*) | .94238 | .000 | -13.9831 | -7.1176 |
| | MHUASB;2 day-high | -7.4799(*) | 1.01346 | .000 | -11.1715 | -3.7883 |
| | THUASB;3 day-low | 9.0386(*) | 1.32547 | .000 | 4.2104 | 13.8668 |
| | THUASB;5 day-high | -11.7476(*) | 1.07178 | .000 | -15.6517 | -7.8435 |
| | THUASB;4 day-high | -6.5531(*) | .97263 | .000 | -10.0960 | -3.0101 |
| | THUASB;3 day-high | -4.4647(*) | .97263 | .002 | -8.0076 | -.9218 |
| | THUASB;2 day-high | .9711 | 1.01346 | 1.000 | -2.7205 | 4.6627 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| TUASB;2 day-high | MUASB;5 day-low | -19.7793(*) | 1.22715 | .000 | -24.2493 | -15.3093 |
| | MUASB;3 day-low | -19.0719(*) | .99899 | .000 | -22.7109 | -15.4330 |
| | MUASB;5 day-high | -24.5537(*) | 1.19122 | .000 | -28.8929 | -20.2146 |
| | MUASB;4 day-high | -18.9679(*) | 1.22715 | .000 | -23.4379 | -14.4978 |
| | MUASB;3 day-high | -12.0805(*) | 1.11944 | .000 | -16.1582 | -8.0028 |
| | MUASB;2 day-high | -6.2039(*) | 1.16251 | .000 | -10.4385 | -1.9693 |
| | TUASB;5 day-low | -12.4075(*) | 1.42378 | .000 | -17.5938 | -7.2212 |
| | TUASB;3 day-low | -15.5750(*) | 1.04740 | .000 | -19.3903 | -11.7597 |
| | TUASB;5 day-high | -21.9338(*) | 1.19122 | .000 | -26.2729 | -17.5946 |
| | TUASB;4 day-high | -15.5029(*) | 1.07628 | .000 | -19.4233 | -11.5824 |
| | TUASB;3 day-high | -7.0361(*) | 1.16251 | .000 | -11.2707 | -2.8015 |
| | MHUASB;3 day-low | -20.1533(*) | 1.27347 | .000 | -24.7921 | -15.5146 |
| | MTUASB;5 day-high | -25.7688(*) | 1.19122 | .000 | -30.1079 | -21.4296 |
| | MHUASB;4 day-high | -21.5729(*) | 1.07628 | .000 | -25.4933 | -17.6524 |
| | MHUASB;3 day-high | -17.5864(*) | 1.07628 | .000 | -21.5069 | -13.6660 |
| | MHUASB;2 day-high | -14.5160(*) | 1.13903 | .000 | -18.6650 | -10.3670 |
| | THUASB;3 day-low | 2.0025 | 1.42378 | .999 | -3.1838 | 7.1888 |
| | THUASB;5 day-high | -18.7838(*) | 1.19122 | .000 | -23.1229 | -14.4446 |
| | THUASB;4 day-high | -13.5892(*) | 1.10286 | .000 | -17.6064 | -9.5719 |
| | THUASB;3 day-high | -11.5008(*) | 1.10286 | .000 | -15.5181 | -7.4836 |
| | THUASB;2 day-high | -6.0650(*) | 1.13903 | .000 | -10.2140 | -1.9160 |
| MHUASB;3 day-low | MUASB;5 day-low | .3740 | 1.22715 | 1.000 | -4.0960 | 4.8441 |
| | MUASB;3 day-low | 1.0814 | .99899 | 1.000 | -2.5575 | 4.7204 |
| | MUASB;5 day-high | -4.4004(*) | 1.19122 | .043 | -8.7396 | -.0613 |
| | MUASB;4 day-high | 1.1855 | 1.22715 | 1.000 | -3.2845 | 5.6555 |
| | MUASB;3 day-high | 8.0729(*) | 1.11944 | .000 | 3.9952 | 12.1506 |
| | MUASB;2 day-high | 13.9494(*) | 1.16251 | .000 | 9.7149 | 18.1840 |
| | TUASB;5 day-low | 7.7458(*) | 1.42378 | .000 | 2.5595 | 12.9321 |
| | TUASB;3 day-low | 4.5783(*) | 1.04740 | .004 | .7631 | 8.3936 |
| | TUASB;5 day-high | -1.7804 | 1.19122 | .997 | -6.1196 | 2.5587 |
| | TUASB;4 day-high | 4.6505(*) | 1.07628 | .005 | .7300 | 8.5709 |
| | TUASB;3 day-high | 13.1172(*) | 1.16251 | .000 | 8.8826 | 17.3518 |
| | TUASB;2 day-high | 20.1533(*) | 1.27347 | .000 | 15.5146 | 24.7921 |
| | MTUASB;5 day-high | -5.6154(*) | 1.19122 | .001 | -9.9546 | -1.2763 |
| | MHUASB;4 day-high | -1.4195 | 1.07628 | .999 | -5.3400 | 2.5009 |
| | MHUASB;3 day-high | 2.5669 | 1.07628 | .717 | -1.3536 | 6.4874 |
| | MHUASB;2 day-high | 5.6373(*) | 1.13903 | .000 | 1.4883 | 9.7864 |
| | THUASB;3 day-low | 22.1558(*) | 1.42378 | .000 | 16.9695 | 27.3421 |
| | THUASB;5 day-high | 1.3696 | 1.19122 | 1.000 | -2.9696 | 5.7087 |
| | THUASB;4 day-high | 6.5642(*) | 1.10286 | .000 | 2.5469 | 10.5814 |
| | THUASB;3 day-high | 8.6525(*) | 1.10286 | .000 | 4.6352 | 12.6698 |
| | THUASB;2 day-high | 14.0883(*) | 1.13903 | .000 | 9.9393 | 18.2374 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MTUASB;5 day-high | MUASB;5 day-low | 5.9895(*) | 1.14156 | .000 | 1.8312 | 10.1477 |
| | MUASB;3 day-low | 6.6968(*) | .89178 | .000 | 3.4484 | 9.9452 |
| | MUASB;5 day-high | 1.2150 | 1.10286 | 1.000 | -2.8023 | 5.2323 |
| | MUASB;4 day-high | 6.8009(*) | 1.14156 | .000 | 2.6426 | 10.9592 |
| | MUASB;3 day-high | 13.6883(*) | 1.02491 | .000 | 9.9550 | 17.4216 |
| | MUASB;2 day-high | 19.5649(*) | 1.07178 | .000 | 15.6608 | 23.4690 |
| | TUASB;5 day-low | 13.3613(*) | 1.35072 | .000 | 8.4411 | 18.2814 |
| | TUASB;3 day-low | 10.1938(*) | .94569 | .000 | 6.7490 | 13.6385 |
| | TUASB;5 day-high | 3.8350 | 1.10286 | .082 | -.1823 | 7.8523 |
| | TUASB;4 day-high | 10.2659(*) | .97758 | .000 | 6.7050 | 13.8268 |
| | TUASB;3 day-high | 18.7326(*) | 1.07178 | .000 | 14.8285 | 22.6367 |
| | TUASB;2 day-high | 25.7688(*) | 1.19122 | .000 | 21.4296 | 30.1079 |
| | MHUASB;3 day-low | 5.6154(*) | 1.19122 | .001 | 1.2763 | 9.9546 |
| | MHUASB;4 day-high | 4.1959(*) | .97758 | .005 | .6350 | 7.7568 |
| | MHUASB;3 day-high | 8.1823(*) | .97758 | .000 | 4.6214 | 11.7433 |
| | MHUASB;2 day-high | 11.2528(*) | 1.04626 | .000 | 7.4416 | 15.0639 |
| | THUASB;3 day-low | 27.7713(*) | 1.35072 | .000 | 22.8511 | 32.6914 |
| | THUASB;5 day-high | 6.9850(*) | 1.10286 | .000 | 2.9677 | 11.0023 |
| | THUASB;4 day-high | 12.1796(*) | 1.00677 | .000 | 8.5123 | 15.8468 |
| | THUASB;3 day-high | 14.2679(*) | 1.00677 | .000 | 10.6007 | 17.9352 |
| | THUASB;2 day-high | 19.7038(*) | 1.04626 | .000 | 15.8926 | 23.5149 |
| MHUASB;4 day-high | MUASB;5 day-low | 1.7936 | 1.02105 | .979 | -1.9257 | 5.5129 |
| | MUASB;3 day-low | 2.5009 | .73119 | .097 | -.1625 | 5.1644 |
| | MUASB;5 day-high | -2.9809 | .97758 | .246 | -6.5418 | .5800 |
| | MUASB;4 day-high | 2.6050 | 1.02105 | .593 | -1.1143 | 6.3243 |
| | MUASB;3 day-high | 9.4924(*) | .88871 | .000 | 6.2552 | 12.7296 |
| | MUASB;2 day-high | 15.3690(*) | .94238 | .000 | 11.9362 | 18.8017 |
| | TUASB;5 day-low | 9.1654(*) | 1.25052 | .000 | 4.6102 | 13.7205 |
| | TUASB;3 day-low | 5.9979(*) | .79605 | .000 | 3.0981 | 8.8976 |
| | TUASB;5 day-high | -.3609 | .97758 | 1.000 | -3.9218 | 3.2000 |
| | TUASB;4 day-high | 6.0700(*) | .83368 | .000 | 3.0332 | 9.1068 |
| | TUASB;3 day-high | 14.5367(*) | .94238 | .000 | 11.1040 | 17.9695 |
| | TUASB;2 day-high | 21.5729(*) | 1.07628 | .000 | 17.6524 | 25.4933 |
| | MHUASB;3 day-low | 1.4195 | 1.07628 | .999 | -2.5009 | 5.3400 |
| | MTUASB;5 day-high | -4.1959(*) | .97758 | .005 | -7.7568 | -.6350 |
| | MHUASB;3 day-high | 3.9864(*) | .83368 | .001 | .9496 | 7.0232 |
| | MHUASB;2 day-high | 7.0569(*) | .91325 | .000 | 3.7302 | 10.3835 |
| | THUASB;3 day-low | 23.5754(*) | 1.25052 | .000 | 19.0202 | 28.1305 |
| | THUASB;5 day-high | 2.7891 | .97758 | .367 | -.7718 | 6.3500 |
| | THUASB;4 day-high | 7.9837(*) | .86772 | .000 | 4.8229 | 11.1445 |
| | THUASB;3 day-high | 10.0720(*) | .86772 | .000 | 6.9112 | 13.2328 |
| | THUASB;2 day-high | 15.5079(*) | .91325 | .000 | 12.1812 | 18.8345 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| MHUASB;3 day-high | MUASB;5 day-low | -2.1929 | 1.02105 | .862 | -5.9121 | 1.5264 |
| | MUASB;3 day-low | -1.4855 | .73119 | .913 | -4.1489 | 1.1779 |
| | MUASB;5 day-high | -6.9673(*) | .97758 | .000 | -10.5283 | -3.4064 |
| | MUASB;4 day-high | -1.3814 | 1.02105 | .999 | -5.1007 | 2.3379 |
| | MUASB;3 day-high | 5.5060(*) | .88871 | .000 | 2.2688 | 8.7432 |
| | MUASB;2 day-high | 11.3825(*) | .94238 | .000 | 7.9498 | 14.8153 |
| | TUASB;5 day-low | 5.1789(*) | 1.25052 | .009 | .6238 | 9.7341 |
| | TUASB;3 day-low | 2.0114 | .79605 | .612 | -.8883 | 4.9111 |
| | TUASB;5 day-high | -4.3473(*) | .97758 | .003 | -7.9083 | -.7864 |
| | TUASB;4 day-high | 2.0836 | .83368 | .633 | -.9532 | 5.1204 |
| | TUASB;3 day-high | 10.5503(*) | .94238 | .000 | 7.1176 | 13.9831 |
| | TUASB;2 day-high | 17.5864(*) | 1.07628 | .000 | 13.6660 | 21.5069 |
| | MHUASB;3 day-low | -2.5669 | 1.07628 | .717 | -6.4874 | 1.3536 |
| | MTUASB;5 day-high | -8.1823(*) | .97758 | .000 | -11.7433 | -4.6214 |
| | MHUASB;4 day-high | -3.9864(*) | .83368 | .001 | -7.0232 | -.9496 |
| | MHUASB;2 day-high | 3.0704 | .91325 | .113 | -.2562 | 6.3971 |
| | THUASB;3 day-low | 19.5889(*) | 1.25052 | .000 | 15.0338 | 24.1441 |
| | THUASB;5 day-high | -1.1973 | .97758 | 1.000 | -4.7583 | 2.3636 |
| | THUASB;4 day-high | 3.9973(*) | .86772 | .001 | .8365 | 7.1580 |
| | THUASB;3 day-high | 6.0856(*) | .86772 | .000 | 2.9248 | 9.2464 |
| | THUASB;2 day-high | 11.5214(*) | .91325 | .000 | 8.1948 | 14.8481 |
| MHUASB;2 day-high | MUASB;5 day-low | -5.2633(*) | 1.08699 | .001 | -9.2228 | -1.3038 |
| | MUASB;3 day-low | -4.5559(*) | .82075 | .000 | -7.5456 | -1.5662 |
| | MUASB;5 day-high | -10.0377(*) | 1.04626 | .000 | -13.8489 | -6.2266 |
| | MUASB;4 day-high | -4.4519(*) | 1.08699 | .011 | -8.4113 | -.4924 |
| | MUASB;3 day-high | 2.4355 | .96375 | .612 | -1.0750 | 5.9461 |
| | MUASB;2 day-high | 8.3121(*) | 1.01346 | .000 | 4.6205 | 12.0037 |
| | TUASB;5 day-low | 2.1085 | 1.30492 | .992 | -2.6448 | 6.8618 |
| | TUASB;3 day-low | -1.0590 | .87904 | 1.000 | -4.2610 | 2.1430 |
| | TUASB;5 day-high | -7.4178(*) | 1.04626 | .000 | -11.2289 | -3.6066 |
| | TUASB;4 day-high | -.9869 | .91325 | 1.000 | -4.3135 | 2.3398 |
| | TUASB;3 day-high | 7.4799(*) | 1.01346 | .000 | 3.7883 | 11.1715 |
| | TUASB;2 day-high | 14.5160(*) | 1.13903 | .000 | 10.3670 | 18.6650 |
| | MHUASB;3 day-low | -5.6373(*) | 1.13903 | .000 | -9.7864 | -1.4883 |
| | MTUASB;5 day-high | -11.2528(*) | 1.04626 | .000 | -15.0639 | -7.4416 |
| | MHUASB;4 day-high | -7.0569(*) | .91325 | .000 | -10.3835 | -3.7302 |
| | MHUASB;3 day-high | -3.0704 | .91325 | .113 | -6.3971 | .2562 |
| | THUASB;3 day-low | 16.5185(*) | 1.30492 | .000 | 11.7652 | 21.2718 |
| | THUASB;5 day-high | -4.2678(*) | 1.04626 | .011 | -8.0789 | -.4566 |
| | THUASB;4 day-high | .9268 | .94443 | 1.000 | -2.5134 | 4.3670 |
| | THUASB;3 day-high | 3.0152 | .94443 | .176 | -.4250 | 6.4554 |
| | THUASB;2 day-high | 8.4510(*) | .98642 | .000 | 4.8578 | 12.0442 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| THUASB;3 day-low | MUASB;5 day-low | -21.7818(*) | 1.38250 | .000 | -26.8177 | -16.7459 |
| | MUASB;3 day-low | -21.0744(*) | 1.18466 | .000 | -25.3897 | -16.7592 |
| | MUASB;5 day-high | -26.5562(*) | 1.35072 | .000 | -31.4764 | -21.6361 |
| | MUASB;4 day-high | -20.9704(*) | 1.38250 | .000 | -26.0063 | -15.9344 |
| | MUASB;3 day-high | -14.0830(*) | 1.28786 | .000 | -18.7741 | -9.3918 |
| | MUASB;2 day-high | -8.2064(*) | 1.32547 | .000 | -13.0346 | -3.3782 |
| | TUASB;5 day-low | -14.4100(*) | 1.55967 | .000 | -20.0913 | -8.7287 |
| | TUASB;3 day-low | -17.5775(*) | 1.22576 | .000 | -22.0425 | -13.1125 |
| | TUASB;5 day-high | -23.9363(*) | 1.35072 | .000 | -28.8564 | -19.0161 |
| | TUASB;4 day-high | -17.5054(*) | 1.25052 | .000 | -22.0605 | -12.9502 |
| | TUASB;3 day-high | -9.0386(*) | 1.32547 | .000 | -13.8668 | -4.2104 |
| | TUASB;2 day-high | -2.0025 | 1.42378 | .999 | -7.1888 | 3.1838 |
| | MHUASB;3 day-low | -22.1558(*) | 1.42378 | .000 | -27.3421 | -16.9695 |
| | MTUASB;5 day-high | -27.7713(*) | 1.35072 | .000 | -32.6914 | -22.8511 |
| | MHUASB;4 day-high | -23.5754(*) | 1.25052 | .000 | -28.1305 | -19.0202 |
| | MHUASB;3 day-high | -19.5889(*) | 1.25052 | .000 | -24.1441 | -15.0338 |
| | MHUASB;2 day-high | -16.5185(*) | 1.30492 | .000 | -21.2718 | -11.7652 |
| | THUASB;5 day-high | -20.7863(*) | 1.35072 | .000 | -25.7064 | -15.8661 |
| | THUASB;4 day-high | -15.5917(*) | 1.27347 | .000 | -20.2304 | -10.9529 |
| | THUASB;3 day-high | -13.5033(*) | 1.27347 | .000 | -18.1421 | -8.8646 |
| | THUASB;2 day-high | -8.0675(*) | 1.30492 | .000 | -12.8208 | -3.3142 |
| THUASB;5 day-high | MUASB;5 day-low | -.9955 | 1.14156 | 1.000 | -5.1538 | 3.1627 |
| | MUASB;3 day-low | -.2882 | .89178 | 1.000 | -3.5366 | 2.9602 |
| | MUASB;5 day-high | -5.7700(*) | 1.10286 | .000 | -9.7873 | -1.7527 |
| | MUASB;4 day-high | -.1841 | 1.14156 | 1.000 | -4.3424 | 3.9742 |
| | MUASB;3 day-high | 6.7033(*) | 1.02491 | .000 | 2.9700 | 10.4366 |
| | MUASB;2 day-high | 12.5799(*) | 1.07178 | .000 | 8.6758 | 16.4840 |
| | TUASB;5 day-low | 6.3763(*) | 1.35072 | .001 | 1.4561 | 11.2964 |
| | TUASB;3 day-low | 3.2088 | .94569 | .104 | -.2360 | 6.6535 |
| | TUASB;5 day-high | -3.1500 | 1.10286 | .365 | -7.1673 | .8673 |
| | TUASB;4 day-high | 3.2809 | .97758 | .115 | -.2800 | 6.8418 |
| | TUASB;3 day-high | 11.7476(*) | 1.07178 | .000 | 7.8435 | 15.6517 |
| | TUASB;2 day-high | 18.7838(*) | 1.19122 | .000 | 14.4446 | 23.1229 |
| | MHUASB;3 day-low | -1.3696 | 1.19122 | 1.000 | -5.7087 | 2.9696 |
| | MTUASB;5 day-high | -6.9850(*) | 1.10286 | .000 | -11.0023 | -2.9677 |
| | MHUASB;4 day-high | -2.7891 | .97758 | .367 | -6.3500 | .7718 |
| | MHUASB;3 day-high | 1.1973 | .97758 | 1.000 | -2.3636 | 4.7583 |
| | MHUASB;2 day-high | 4.2678(*) | 1.04626 | .011 | .4566 | 8.0789 |
| | THUASB;3 day-low | 20.7863(*) | 1.35072 | .000 | 15.8661 | 25.7064 |
| | THUASB;4 day-high | 5.1946(*) | 1.00677 | .000 | 1.5273 | 8.8618 |
| | THUASB;3 day-high | 7.2829(*) | 1.00677 | .000 | 3.6157 | 10.9502 |
| | THUASB;2 day-high | 12.7188(*) | 1.04626 | .000 | 8.9076 | 16.5299 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| THUASB;4 day-high | MUASB;5 day-low | -6.1901(*) | 1.04903 | .000 | -10.0113 | -2.3689 |
| | MUASB;3 day-low | -5.4828(*) | .76977 | .000 | -8.2867 | -2.6788 |
| | MUASB;5 day-high | -10.9646(*) | 1.00677 | .000 | -14.6318 | -7.2973 |
| | MUASB;4 day-high | -5.3787(*) | 1.04903 | .000 | -9.1999 | -1.5575 |
| | MUASB;3 day-high | 1.5087 | .92072 | .991 | -1.8451 | 4.8625 |
| | MUASB;2 day-high | 7.3853(*) | .97263 | .000 | 3.8424 | 10.9282 |
| | TUASB;5 day-low | 1.1817 | 1.27347 | 1.000 | -3.4571 | 5.8204 |
| | TUASB;3 day-low | -1.9858 | .83164 | .715 | -5.0152 | 1.0435 |
| | TUASB;5 day-high | -8.3446(*) | 1.00677 | .000 | -12.0118 | -4.6773 |
| | TUASB;4 day-high | -1.9137 | .86772 | .832 | -5.0745 | 1.2471 |
| | TUASB;3 day-high | 6.5531(*) | .97263 | .000 | 3.0101 | 10.0960 |
| | TUASB;2 day-high | 13.5892(*) | 1.10286 | .000 | 9.5719 | 17.6064 |
| | MHUASB;3 day-low | -6.5642(*) | 1.10286 | .000 | -10.5814 | -2.5469 |
| | MTUASB;5 day-high | -12.1796(*) | 1.00677 | .000 | -15.8468 | -8.5123 |
| | MHUASB;4 day-high | -7.9837(*) | .86772 | .000 | -11.1445 | -4.8229 |
| | MHUASB;3 day-high | -3.9973(*) | .86772 | .001 | -7.1580 | -.8365 |
| | MHUASB;2 day-high | -.9268 | .94443 | 1.000 | -4.3670 | 2.5134 |
| | THUASB;3 day-low | 15.5917(*) | 1.27347 | .000 | 10.9529 | 20.2304 |
| | THUASB;5 day-high | -5.1946(*) | 1.00677 | .000 | -8.8618 | -1.5273 |
| | THUASB;3 day-high | 2.0883 | .90048 | .762 | -1.1918 | 5.3684 |
| | THUASB;2 day-high | 7.5242(*) | .94443 | .000 | 4.0840 | 10.9644 |
| THUASB;3 day-high | MUASB;5 day-low | -8.2785(*) | 1.04903 | .000 | -12.0997 | -4.4573 |
| | MUASB;3 day-low | -7.5711(*) | .76977 | .000 | -10.3751 | -4.7671 |
| | MUASB;5 day-high | -13.0529(*) | 1.00677 | .000 | -16.7202 | -9.3857 |
| | MUASB;4 day-high | -7.4670(*) | 1.04903 | .000 | -11.2882 | -3.6458 |
| | MUASB;3 day-high | -.5796 | .92072 | 1.000 | -3.9334 | 2.7742 |
| | MUASB;2 day-high | 5.2969(*) | .97263 | .000 | 1.7540 | 8.8399 |
| | TUASB;5 day-low | -.9067 | 1.27347 | 1.000 | -5.5454 | 3.7321 |
| | TUASB;3 day-low | -4.0742(*) | .83164 | .000 | -7.1035 | -1.0448 |
| | TUASB;5 day-high | -10.4329(*) | 1.00677 | .000 | -14.1002 | -6.7657 |
| | TUASB;4 day-high | -4.0020(*) | .86772 | .001 | -7.1628 | -.8412 |
| | TUASB;3 day-high | 4.4647(*) | .97263 | .002 | .9218 | 8.0076 |
| | TUASB;2 day-high | 11.5008(*) | 1.10286 | .000 | 7.4836 | 15.5181 |
| | MHUASB;3 day-low | -8.6525(*) | 1.10286 | .000 | -12.6698 | -4.6352 |
| | MTUASB;5 day-high | -14.2679(*) | 1.00677 | .000 | -17.9352 | -10.6007 |
| | MHUASB;4 day-high | -10.0720(*) | .86772 | .000 | -13.2328 | -6.9112 |
| | MHUASB;3 day-high | -6.0856(*) | .86772 | .000 | -9.2464 | -2.9248 |
| | MHUASB;2 day-high | -3.0152 | .94443 | .176 | -6.4554 | .4250 |
| | THUASB;3 day-low | 13.5033(*) | 1.27347 | .000 | 8.8646 | 18.1421 |
| | THUASB;5 day-high | -7.2829(*) | 1.00677 | .000 | -10.9502 | -3.6157 |
| | THUASB;4 day-high | -2.0883 | .90048 | .762 | -5.3684 | 1.1918 |
| | THUASB;2 day-high | 5.4358(*) | .94443 | .000 | 1.9956 | 8.8760 |

Table B.1 (Continued)

| (I) One way | (J) One way | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| THUASB;2 day-high | MUASB;5 day-low | -13.7143(*) | 1.08699 | .000 | -17.6738 | -9.7548 |
| | MUASB;3 day-low | -13.0069(*) | .82075 | .000 | -15.9966 | -10.0172 |
| | MUASB;5 day-high | -18.4887(*) | 1.04626 | .000 | -22.2999 | -14.6776 |
| | MUASB;4 day-high | -12.9029(*) | 1.08699 | .000 | -16.8623 | -8.9434 |
| | MUASB;3 day-high | -6.0155(*) | .96375 | .000 | -9.5260 | -2.5049 |
| | MUASB;2 day-high | -.1389 | 1.01346 | 1.000 | -3.8305 | 3.5527 |
| | TUASB;5 day-low | -6.3425(*) | 1.30492 | .000 | -11.0958 | -1.5892 |
| | TUASB;3 day-low | -9.5100(*) | .87904 | .000 | -12.7120 | -6.3080 |
| | TUASB;5 day-high | -15.8688(*) | 1.04626 | .000 | -19.6799 | -12.0576 |
| | TUASB;4 day-high | -9.4379(*) | .91325 | .000 | -12.7645 | -6.1112 |
| | TUASB;3 day-high | -.9711 | 1.01346 | 1.000 | -4.6627 | 2.7205 |
| | TUASB;2 day-high | 6.0650(*) | 1.13903 | .000 | 1.9160 | 10.2140 |
| | MHUASB;3 day-low | -14.0883(*) | 1.13903 | .000 | -18.2374 | -9.9393 |
| | MTUASB;5 day-high | -19.7038(*) | 1.04626 | .000 | -23.5149 | -15.8926 |
| | MHUASB;4 day-high | -15.5079(*) | .91325 | .000 | -18.8345 | -12.1812 |
| | MHUASB;3 day-high | -11.5214(*) | .91325 | .000 | -14.8481 | -8.1948 |
| | MHUASB;2 day-high | -8.4510(*) | .98642 | .000 | -12.0442 | -4.8578 |
| | THUASB;3 day-low | 8.0675(*) | 1.30492 | .000 | 3.3142 | 12.8208 |
| | THUASB;5 day-high | -12.7188(*) | 1.04626 | .000 | -16.5299 | -8.9076 |
| | THUASB;4 day-high | -7.5242(*) | .94443 | .000 | -10.9644 | -4.0840 |
| | THUASB;3 day-high | -5.4358(*) | .94443 | .000 | -8.8760 | -1.9956 |

Two ways ANOVA for COD concentration

From the two-way ANOVA result, it found that there was a significant effect of reactor type, HRT, and temperature, so it implied that the mean of COD removal varied between the HRT of five, four, three, and two days and the temperature of mesophilic and thermophilic. In addition, there was statistical indication of interaction between HRT and the type of reactor, thus the effect of HRT on the COD removal varied significantly with the variation of reactor. The COD removal differed due to the effect between HRT with temperature and reactor with temperature. The two-way ANOVA result showed the COD removal varied with the effect of three variable operation conditions.

Table B.2 Two-way ANOVA Test of between subject effects with COD removal as dependent variable

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 8557.152(a) | 21 | 407.483 | 83.755 | .000 |
| Intercept | 1154941.707 | 1 | 1154941.707 | 237389.860 | .000 |
| REACTOR | 19.691 | 1 | 19.691 | 4.047 | .046 |
| TEMP | 2433.521 | 1 | 2433.521 | 500.193 | .000 |
| HRT | 4944.458 | 5 | 988.892 | 203.259 | .000 |
| REACTOR * TEMP | 428.646 | 1 | 428.646 | 88.105 | .000 |
| REACTOR * HRT | 1199.891 | 4 | 299.973 | 61.657 | .000 |
| TEMP * HRT | 360.665 | 5 | 72.133 | 14.826 | .000 |
| REACTOR * TEMP * HRT | 419.805 | 4 | 104.951 | 21.572 | .000 |
| Error | 982.764 | 202 | 4.865 | | |
| Total | 1566581.381 | 224 | | | |
| Corrected Total | 9539.916 | 223 | | | |

a R Squared = .897 (Adjusted R Squared = .886)

**APPENDIX C**
**PHOTOS**

Figure C.1 Anaerobic reactors (Armfield Anaerobic Digester W8)

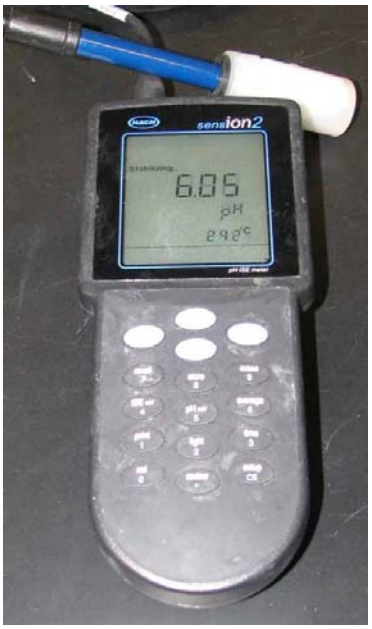


Figure C.2 Hach pH meter (Model Sension 4) using Platinum Series pH Electrode (Model 51910)

Figure C.3 Solids measurement apparatus


Figure C.4 Analytical balance (Mettler Toledo AB204-S)


Figure C.5 Muffle furnace (Nabertherm L15/12/P320)


Figure C.6 (a) Hach digestion reactor, (b) Hach spectrophotometer DR 2000 and high range COD digestion reagent vials


Figure C.7 YSI 5100 Dissolved Oxygen Meter

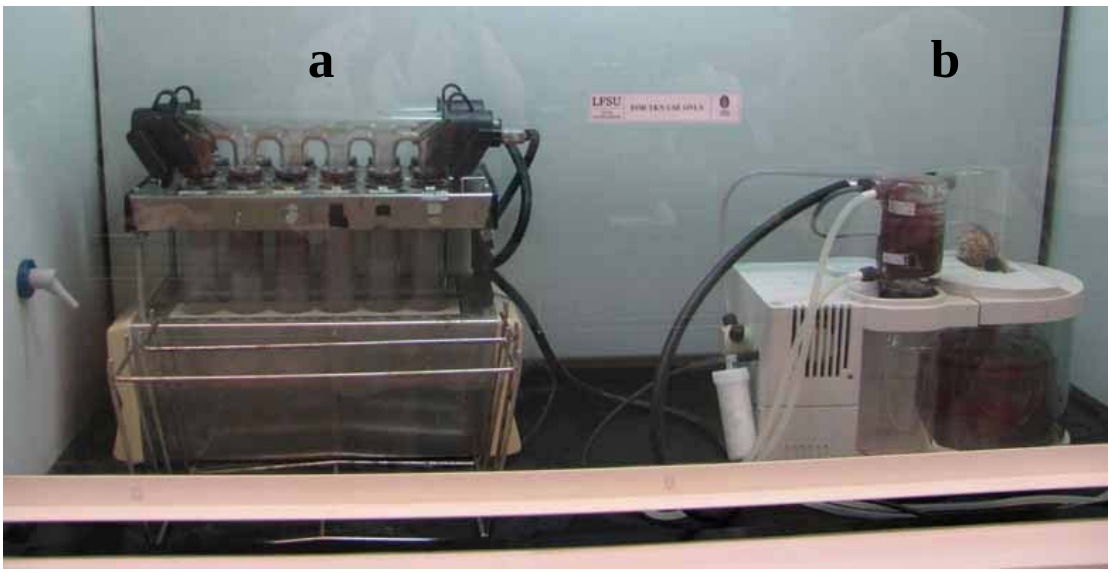


Figure C.8 (a) Buchi K-424 Digestion Unit and (b) Buchi B-414 Scrubber Unit

Figure C.9 Buchi K-314 Distillation Unit

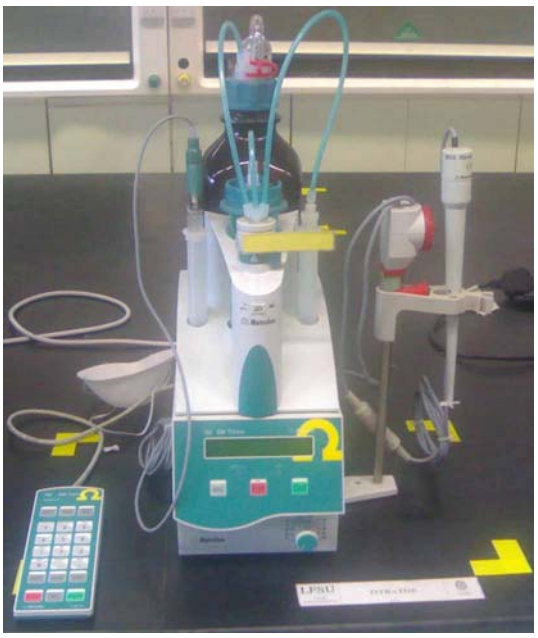

Figure C.10 Auto titration unit (Metrohm 702 SM Titrino)

Figure C.11 Seed biomass from sludge thickener

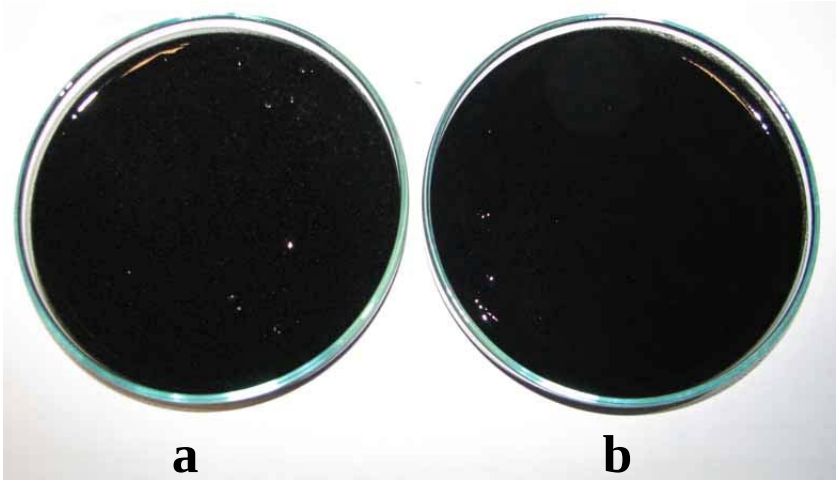


Figure C.12 (a) Mesophilic UASB sludge and (b) thermophilic UASB sludge

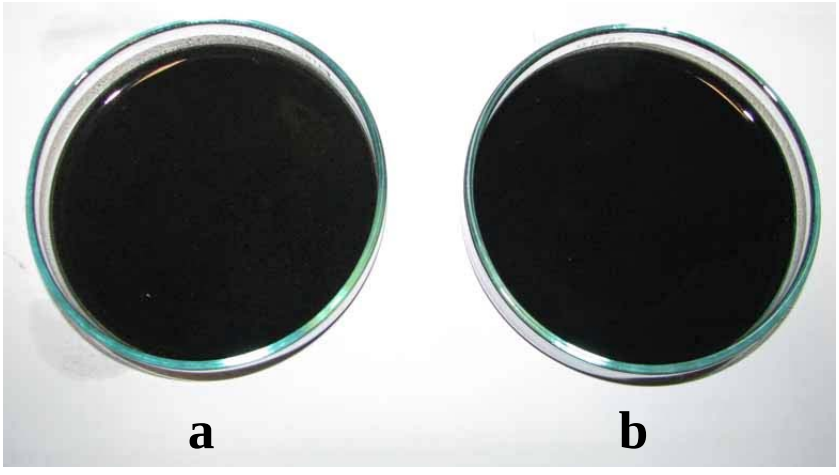


Figure C.13 (a) Mesophilic HUASB sludge and (b) thermophilic HUASB sludge

# VITAE

The author of this thesis, Welly Herumurti, was born on December 23rd, 1981, in Malang, province of East Java, Indonesia. He started his bachelor degree (Sarjana Teknik/ST.) in Department of Environmental Engineering in 2000 at Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia and he obtained his degree in 2005. His final year project report was on the nutrient removal of sewage wastewater using sub-surface (SSF) constructed wetlands. He was appointed as staff at Department of Environmental Engineering ITS Surabaya in 2006. His master degree was started officially in 2007 at the Department of Civil Engineering Universiti Teknologi PETRONAS (UTP) Malaysia. He obtained allowance under Graduate Assistantship (GA) scheme to do a Master of Science (M.Sc.) in Civil Engineering, specialization Environmental Engineering in UTP Malaysia.

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