EFFECTS OF HIGH TEMPERATURE AND LOW CARBON FEED ON BIOLOGICAL PHOSPHORUS REMOVAL

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EFFECTS OF HIGH TEMPERATURE AND LOW CARBON FEED ON BIOLOGICAL PHOSPHORUS REMOVAL

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ABSTRACT

This study was divided into two main parts. The first part was to observe the biological phosphorus removal (BPR) performance at Chongnonsi Wastewater Treatment Plant (WWTP). During investigation period, temperature of mixed liquor and influent Chemical Oxygen Demand (COD) concentration varied in the range of 23-30°C and 60 to 150 mg/l, respectively. At lower temperatures (23-25°C) the phosphorus removal efficiencies, phosphorus contents and percentage of intracellular PHAs were higher than those obtained at higher temperatures (28-30°C), when similar COD and phosphorus concentrations were fed. The significant increase of BPR performance was clearly found when higher COD and phosphorus concentrations were fed, in comparison with lower ones under similar temperature. Low specific phosphorus release rate and specific phosphorus uptake rate were obtained from batch tests, illustrating a weak BPR performance.

In the second part, two SBR reactors, R1 and R2, were used. The reactor R1 was operated at a controlled temperature of 20 °C, while the reactor R2 was gradually altered to 30°C. Five consecutive phases of operation were employed to investigate effects of temperature and low carbon feed on BPR. It was found that the highest phosphorus removal efficiency was in the first phase of operation at 20°C and phosphorus content was found at 11% of TSS, which subsequently decreased to 8% at 30 °C. However, a fair phosphorus removal of about 50% was still observed at the operating temperature of 30 °C. Obviously, the weak BPR performance occurred when low carbon feeds (both in synthetic and real domestic wastewaters) were used. Therefore, low carbon concurrently with low phosphorus in the feed could significantly deteriorate the BPR performance. In the fifth phase of CASS-like operation with real domestic wastewater, phosphorus removal efficiency at 30°C condition was approximately 50%, which were similar to those found in Chongnonsi WWTP.

These findings suggest that both temperature and low carbon feed affect the BPR performance, with greater influence from the low carbon feed than the temperature. In order to enhance the BPR performance in the Chongnonsi Wastewater Treatment Plant, addition of external carbon is recommended.

KEY WORDS: PAOs / BPR PERFORMANCE / TEMPERATURE EFFECT / CARBON FEED / CHONGNONSI WASTEWATER TREATMENT PLANT

186 pp.

ผลของอุณหภูมิสูงและปริมาณคาร์บอนต่ำที่ส่งผลต่อการกำจัดฟอสฟอรัสทางชีวภาพ
(EFFECTS OF HIGH TEMPERATURE AND LOW CARBON FEED ON BIOLOGICAL PHOSPHORUS REMOVAL)

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาถึงผลของอุณหภูมิสูงและปริมาณคาร์บอนต่ำที่ส่งผลต่อการกำจัดฟอสฟอรัสทางชีวภาพ การศึกษาครั้งนี้ได้แบ่งออกเป็นสองส่วนด้วยกัน

ส่วนที่หนึ่งเป็นการติดตามตรวจสอบการกำจัดฟอสฟอรัสทางชีวภาพของโรงควบคุมคุณภาพน้ำช่องนนทรี ผลการศึกษาพบว่า อุณหภูมิและค่าซีโอดีของน้ำเสียที่ป้อนเข้าโรงควบคุมคุณภาพน้ำช่องนนทรี มีความแปรผันอยู่ในช่วง 23-30 องศาเซลเซียส และ 60-150 มิลลิกรัมต่อลิตร ตามลำดับ ในช่วงที่มีอุณหภูมิค่อนข้างต่ำ (23-25 องศาเซลเซียส) ประสิทธิภาพการบำบัดฟอสฟอรัส, เปอร์เซ็นต์การสะสมฟอสฟอรัสและพีเอชเอในเซลล์มีค่าสูงกว่าที่อุณหภูมิสูง (28-30 องศาเซลเซียส) เมื่อความเข้มข้นของซีโอดีและฟอสฟอรัสในน้ำเสียมีค่าใกล้เคียงกัน และพบว่า ในการเดินระบบในช่วงที่มีอุณหภูมิเท่ากัน การกำจัดฟอสฟอรัสทางชีวภาพมีค่าเพิ่มขึ้นอย่างมีนัยสำคัญเมื่อความเข้มข้นของซีโอดีและฟอสฟอรัสในน้ำเสียมีค่าเพิ่มขึ้น ผลการทดลองแบบแบตช์ พบว่าค่าอัตราการปลดปล่อยฟอสฟอรัสจำเพาะ (SPRR) และ ค่าอัตราการจับใช้ฟอสฟอรัสจำเพาะ (SPUR) มีค่าค่อนข้างต่ำซึ่งบ่งชี้ให้เห็นว่าการกำจัดฟอสฟอรัสทางชีวภาพมีค่าค่อนข้างน้อย

ผลการศึกษา ในส่วนที่สองโดยใช้ระบบเอสบีอาร์ ซึ่งประกปบด้วยถังปฏิกรณ์ R1และ R2 โดยถังปฏิกรณ์ที่หนึ่ง (R1) ควบคุมอุณหภูมิที่ 20 องศาเซลเซียส ส่วน ถังปฏิกรณ์ที่สอง (R2) ควบคุมอุณหภูมิที่ 30 องศาเซลเซียส แบ่งการทดลองออกเป็นห้าขั้นตอนด้วยกัน จากผลการทดลองพบว่าที่ 20 องศาเซลเซียส ประสิทธิภาพการกำจัดฟอสฟอรัสสูงที่สุด มีการสะสมฟอสฟอรัสในเซลล์สูงถึงร้อยละ 11 และลดลงมาที่ร้อยละ 8 เมื่อเดินระบบที่อุณหภูมิ 30 องศาเซลเซียส อย่างไรก็ตาม พบการกำจัดฟอสฟอรัสทางชีวภาพในระดับสูงพอสมควรซึ่งประสิทธิภาพการกำจัดฟอสฟอรัสประมาณร้อยละ 50ในการเดินระบบที่อุณหภูมิ 30 องศาเซลเซียสการกำจัดฟอสฟอรัสทางชีวภาพลดต่ำลงอย่างชัดเจนเมื่อใช้น้ำเสียที่มีปริมาณคาร์บอนและฟอสฟอรัสต่ำ ในการทดลองขั้นตอนสุดท้ายที่เดินระบบให้คล้ายคลึงกับระบบ CASS ของโรงควบคุมคุณภาพน้ำช่องนนทรีและใช้น้ำเสียจริงที่อุณหภูมิ 30 องศาเซลเซียส ประสิทธิภาพการกำจัดฟอสฟอรัสลดลงเหลือร้อยละ 50 โดยประมาณ ซึ่งคล้ายคลึงกับที่เกิดขึ้นในโรงควบคุมคุณภาพน้ำช่องนนทรี

ดังนั้น สรุปได้ว่า ทั้งอุณหภูมิที่สูงขึ้นและคาร์บอนต่ำส่งผลต่อการกำจัดฟอสฟอรัสทางชีวภาพ แต่คาร์บอนที่ต่ำส่งผลกระทบมากกว่าอุณหภูมิที่สูงขึ้น ดังนั้น ข้อเสนอแนะในการเพิ่มการกำจัดฟอสฟอรัสทางชีวภาพให้สูงขึ้นในโรงควบคุมคุณภาพน้ำช่องนนทรีควรทำโดยการเพิ่มแหล่งคาร์บอนในน้ำเสียเป็นสำคัญ

186 หน้า

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

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LIST OF ABBREVIATION

CASS	Cyclic Activated Sludge System
Chongnonsi WWTP	Chongnonsi Wastewater Treatment Plant
EBPR	Enhance Biological Phosphorus Removal
GAOs	Glycogen Accumulating Organisms
PAOs	Polyphosphate Accumulating Organisms
PHAs	PolyHydroxyAlkanoates
MLSS	Mix Liquor Suspended Solid
MLVSS	Mix Liquor Volatile Suspended Solid
OHOs	Ordinary heterotrophic Organisms
R1	Reactor 1
R2	Reactor 2
SBR	Sequence Batch Reactor
SCFAs	Short Chain Fatty Acids
SPRR	Specific Phosphorus Release Rate
SPUR	Specific Phosphorus Uptake Rate
SRT	Solid Retention Time
SVI	Sludge Volume Index
VFA	Volatile Fatty Acid
°C	Degree Celsius

CHAPTER I
INTRODUCTION

1.1 Rationales and Justification

Chongnonsi Wastewater Treatment Plant is located in Yannawa district restricted site within the city of Bangkok, Thailand. This plant was commissioned in December 2000 by Bangkok Metropolitan Administrator (BMA). The maximum capacity is 200,000 m^3/day to serve about 28.5 m^2 drainage area, including Sathorn, Yannawa, Bangkholam and Bangrak districts (Figure 1.1.1). The wastewater collection length is 55 kilometers with three pumping stations located at Wat Dan on Rama 3 road, Taksin bridge on Chareornkrung road and at Chongnonsi canal in Sathorn crossroad. Treated effluent is directly discharged into Chaopraya River.

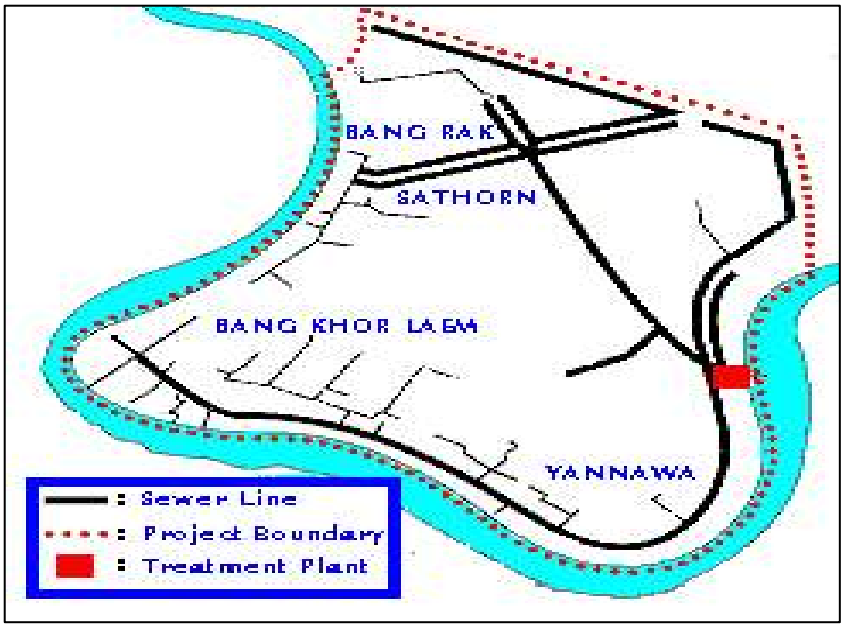


Figure 1.1.1 Sewer line and service area of Chong-nonsi Wastewater treatment Plant.

(Source: http://dds.bma.go.th/yannawa.htm, 27 October 2006)

Chongnonsi wastewater treatment plant consists of preliminary treatment for refuse and solids separation, and secondary treatment which was designed as a BNR (biological nutrient removal) system. The system used for secondary treatment is a type of activated sludge system called “Cyclic Activated Sludge System (CASS)”, which is developed from Sequencing Batch Reactor System (SBR). CASS is implemented in four floors building; each floor contains six CASS basins, total 24 reactors in Chongnonsi WWTP. Each CASS basin is divided into three zones, the first zone is where influent passed through and distributed to other zones, anaerobic condition occurred because of no aeration in this zone. The second and the third zones are operated as anoxic and aerobic conditions in order to remove nitrogen and phosphorus biologically.

However, the performance of Chongnonsi Wastewater Treatment Plant during January to March 2002 was reported that the efficiencies of BOD removal and suspended solid removal were both more than 90%, but nitrogen and phosphorus removal were have only 40% and 32% efficiencies (BMA, 2004).

The characteristics of wastewater entering Chongnonsri Wastewater treatment Plant was shown in Table 1.1.1. The average BOD concentration is 33 mg/l, and average nitrogen and phosphorus concentrations are 9.1 and 2.3 mg/l, respectively. Thus, ratios of BOD:nitrogen and BOD:phosphorus are 3.6 and 14 , respectively. In this case, amount of carbon is considered too little for bacteria to use and store within their cells, which affects the abilities of phosphorus uptaking and releasing, and consequently, the phosphorus removal efficiency.

Table 1.1.1 Characteristics of domestic wastewater entering Chongnonsi Wastewater treatment Plant (BMA, 2004).

Values	Flow rate (m^3/d)	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TN (mg/l)	TP (mg/l)
Minimum	93,394	18.8	27	13	4.7	1.2
Average	129,171	33.2	75	54	9.1	2.3
Maximum	166,862	83.3	225	254	18	6.8

In addition, the temperature can affect on biological phosphorus removal. Duangjai (2003) reported that the efficiency of biological phosphorus removal was lessened at higher temperature, especially at higher than 30 ^{o}C, the efficiency of biological phosphorus removal was less than 40 %

Thus, this study will investigate biological phosphorus removal occurrence in Thailand, using Chongnonsi Wastewater Treatment Plant as a case study, to define any cause of low phosphorus removal efficiency and recommend the solution to increase phosphorus removal efficiency.

1.2 Research Objectives

1.2.1 General Objective

To investigate the occurrence and possibility of biological phosphorus removal in Thailand, using Chongnonsi Wastewater Treatment Plant as a case study.

1.2.2 Specific Objectives

1) To investigate the effect of temperature on biological phosphorus removal in Thailand, using Chongnonsi Wastewater Treatment Plant as a case study.

2) To investigate the effect of low - carbon domestic wastewater on biological phosphorus removal in Thailand, using Chongnonsi Wastewater Treatment Plant.

1.3 Research Hypotheses

1) Higher temperature would reduce biological phosphorus removal efficiency.
2) Low Carbon source would reduce biological phosphorus removal efficiency.

1.4 Research Variables

This research was divided into two parts; the one was a field study at Chongnonsi Wastewater Treatment Plant and the other is an experiment with lab-scale SBRs in the laboratory. Conceptual framework is shown in Figure 1.3.

1.4.1 The first part: The investigation of biological phosphorus removal occurrence in Chongnonsi Wastewater Treatment Plant.

Independent variables: -Bangkok seasonal temperature
-Wastewater Characteristics
Dependent variables: -Phosphorus removal efficiency
-COD removal efficiency
Control variables: -Configuration of CASS operation
-CASS reactors for sampling

1.4.2 The second part: The investigation of biological phosphorus removal in lab-scale SBR, imitation of Chongnonsi Wastewater Treatment Plant.

Independent variables: -Water temperatures of 20^{o}C and room temperature
-Wastewater Characteristics
Dependent variables: -Phosphorus removal efficiency
-COD removal efficiency
Control variables: -Size of lab-scale SBRs
-Operating conditions

1.5 Scope of Study

1.5.1 For the first part, which was a field study with Chongnonsi Wastewater Treatment Plant, the investigation was done during the season of lower temperature winter and higher temperature summer of Thailand. Wastewater entering into this plant would be seasonally varied. Some reactors of the plant would be selected for this study.

1.5.2 In the second part, a lab-scale SBR system would be applied for this experiment. The operation would be started with wastewater and operating conditions, which are suitable for biological phosphorus removal (BPR) to occur. Then, temperature effect would be tested on the BPR performance in this lab-scale reactor. After that, the effect of low carbon source in real wastewater (the same one entering Chongnonsi Wastewater Treatment Plant) would be further studied.

1.6 Limitation of Study

1.6.1 Domestic wastewater entering to Chongnonsi Wastewater Treatment Plant would be collected only three times per week.

1.6.2 The filed study would be conducted only with some CASS reactors of this plant.

1.6.3 An operation cycle of a lab-scale SBR would not be exactly the same as that of CASS in Chongnonsi Wastewater Treatment Plant because of their configuration difference. The most similar operation would be attempted to imitate the performance of CASS.

1.7 Definition of Keywords

1.7.1 Biological Phosphorus Removal is defined as a wastewater treatment configuration applied to activated sludge systems for the removal of phosphate. The common element in EBPR implementations is the presence of an anaerobic tank (nitrate and oxygen are absent) prior to the aeration tank.

1.7.2. **Polyphosphate-Acumulating Organisms (PAOs)** is defined as a group of heterotrophic bacteria, called polyphosphate-accumulating organisms (PAO), are selectively enriched in the bacterial community within the activated sludge. These bacteria accumulate large quantities of polyphosphate within their cells and the removal of phosphorus is said to be *enhanced*

1.7.3. **Domestic Wastewater** is defined as the spent water origination from all aspects of household water used. It typically constitutes a combination of flow from the kitchen, bathroom, toilets, laundry, dishwashers and washing machines. It is a subpart of municipal wastewater.

1.7.4. Primary Sludge is defined as all those solids, which settle to the bottle of the primary sedimentation tank of wastewater treatment plant. It is possibly composed of 40-80% of volatile matters and the organic matters may include fat and grease, food residues, faeces and paper.

1.7.5 Volatile Fatty Acid is defined as a product of the acid fermentation. It is mainly short chain fatty acids with two to five carbon (C_2-C_5) atoms, which most of them found in wastewater treatment system are acetic acid, propionic acid and butyric acid.

1.7.6 Mixed Liquor Suspended Solids (MLSS) is the concentration of suspended solid in mixed liquor, expressed in milligrams per liter (mg/l).

1.8 Conceptual Framework

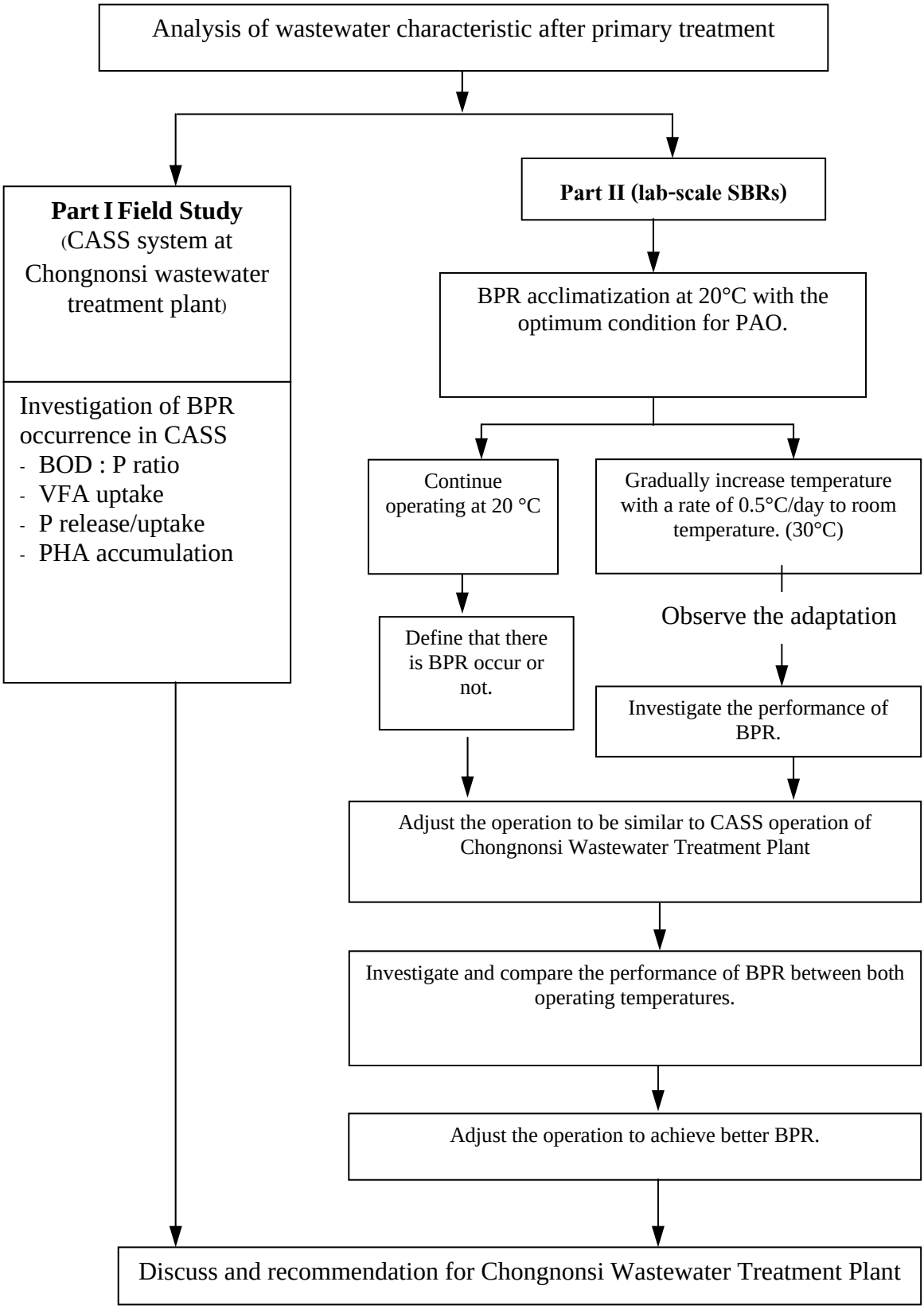


Figure 1.8.1 Conceptual Framework

CHAPTER II
LITERATURE REVIEWS

2.1 Chongnonsi Wastewater Treatment Plant

2.1.1 Project background

Chongnonsi Wastewater Treatment Plant is one in a series of large wastewater treatment facilities constructed in Bangkok area. Its serviced area of 28.5 km^2 included Sathorn, Yannawa, Bangkholaem and Bangrak districts. This plant was firstly operated since December 1999 by Metropolitant Autrority (BMA). The collection system of this plant was a combine sewer system, connected to a current drainage system of BMA. Inceptor chambers were constructed to collected wastewater before directly draining to any canals or Chao Phraya River. Wastewater arrives at the treatment plant site via a 2.25 m. diameter gravity sewer. Sewer system longed about 51 km and three sewage lift pumping stations were provided to avoid sewer depths greater than 15 m.

The treatment plant was constructed in a four-store building because of limitation of land availability and to minimize environmental and visual impact. Treatment process was claimed to be flexible for treating a range of influent wastewater concentrations, and includes nutrient removal process (Kirkwood, 2004). The selected secondary treatment process was based on sequencing batch reactor technology using the CASS^{TM} process variant. This process was easily adaptable to a multistory configuration and compatible with surrounding area. Also, it was easily constructed as a rectangular process, which its capability was proved for providing the required final effluent quality.

The treatment plant site only covers 28,000 m^2, which around half was subject to daily flooding from the Chao Phraya River. The site's northern boundary adjoin

one of the major Chongnonsi canal, whilst to the west and south it abuts land owned, as illustrated in Figure 2.1.1.

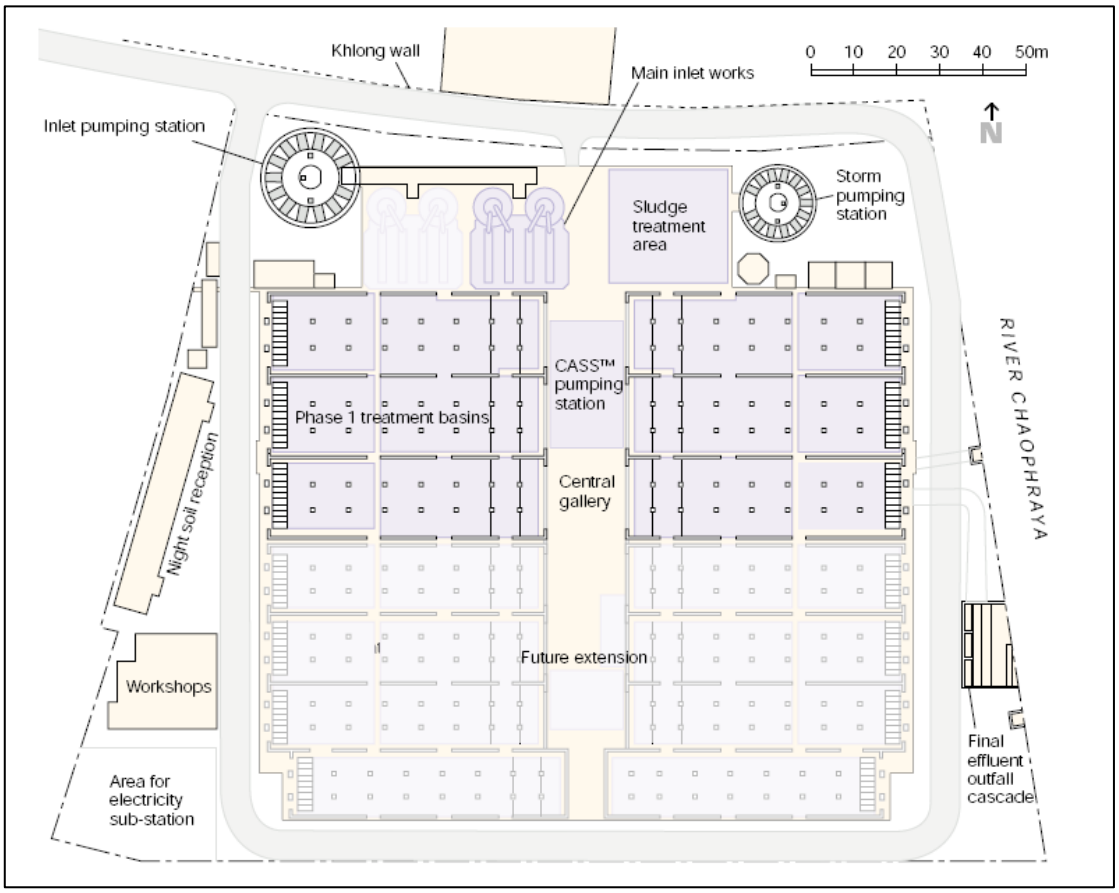


Figure 2.1.1 The plan of Chongnonsi wastewater treatment plant. (Senior, 2000).

The processes in this plant composed of three treatment steps, i.e., preliminary treatment, secondary treatment and sludge treatment and process diagram of Chongnonsi WWTP as illustrated in Figure 2.1.2 and Figure.2.1.3

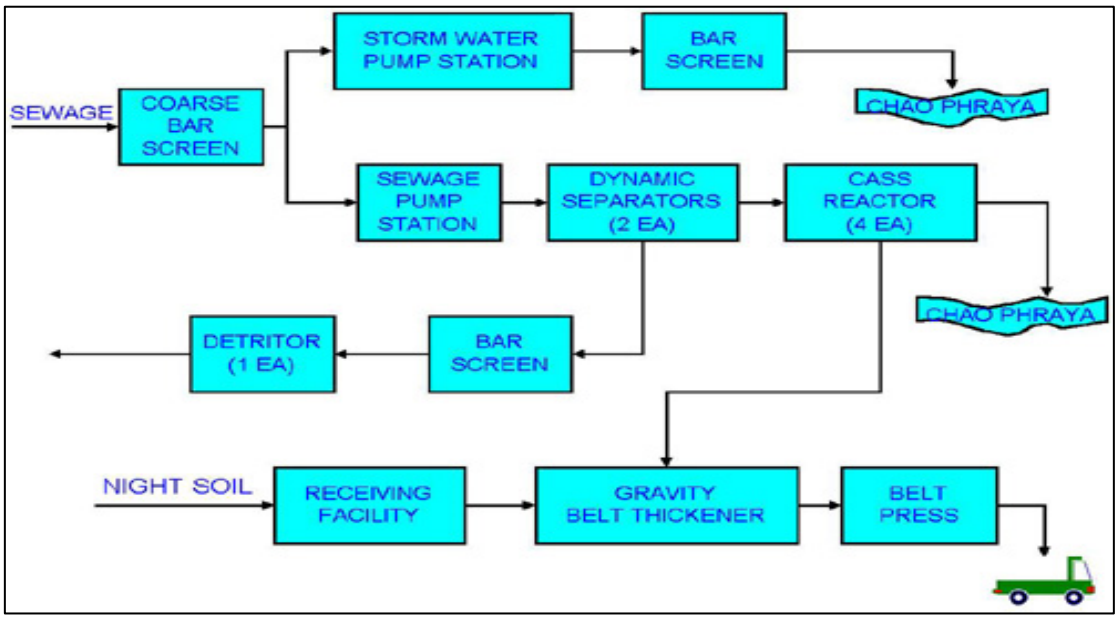


Figure 2.1.2 Schematic flow in Chongnonsi Wastewater Treatment Plant. (Source: http://dds.bma.go.th/yannawa.htm, 27 October 2006)

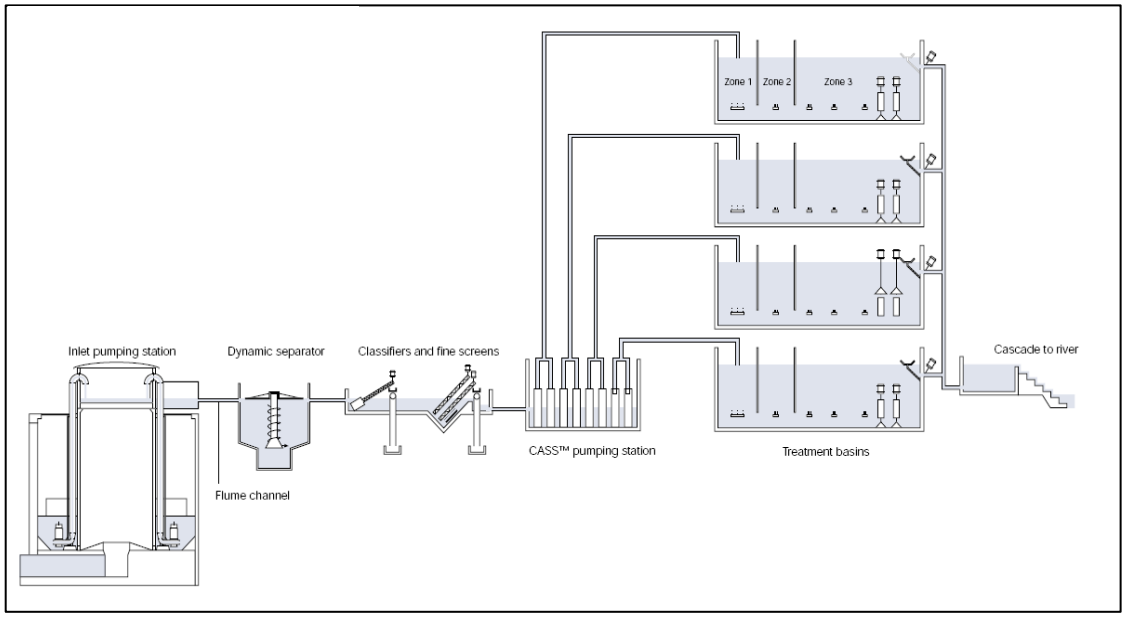


Figure 2.1.3 The process flow diagram of Chongnonsi WWTP (Senior, 2000).

For **Preliminary treatment**, an inlet pumping station was provided for all flows up to 500,000 m^3/day with seven submersible pumps, controlled on level in the pumping station wet well. All flows in excess of 500,000 m^3/day are transferred by gravity to a separate storm water pumping 3wstation. Flows from the inlet pumping station pass through two dynamic separators, operated as duty/assist. Inflows above a set point automatically bring the assist dynamic separator into use. Grit, sand and larger screenings were removed in the dynamic separators and transferred by the underflow pumps to underflow streams. Four underflow pumps were provided in total, two in each dynamic separator, operating as duty according to increasing or decreasing flows. The remaining flow through each dynamic separator overflows into a band screen channel. Four underflow streams were provided, each stream being normally dedicated to an underflow pump. Each underflow stream consists of a fine drum screen with integral compacting screw conveyor, controlled on differential level, followed by a grit classifier equipped with two dewatering screws. Screenings and grit removed in the underflow streams were transported to skips via belt conveyors. Two 5 mm band screens were provided to treat the overflow from the dynamic separators, one screen per separator. Screenings removed by the fine screens are dewatered in a screw compactor then discharged onto a belt conveyor and transferred to skips.

The dynamic separators, the underflow pumps, the underflow streams and the band screens together comprised the preliminary treatment units and are controlled according to the number of inlet pumps that are in operation. The flow from the band screen channels gravitates into a flow separation chamber from where flows of 300,000 m^3 per day was excess in phase 1, are diverted to a river outfall by two actuated weir penstocks. Flow separation is controlled by level. The flows up to 300,000 m^3 per day at phase 1 then pass into a pumping station, which delivers wastewater to the SBR secondary treatment units. This consists of a conventional four-way distribution chamber based on overflow weirs. Downstream of each overflow weir was a wet well which is dedicated to one floor of the four-storied sequencing batch reactor (SBR) plant. Each wet well is provided with duty/assist/assist submersible pumps and lifts the wastewater to a distribution manifold to ensure equal distribution into the six compartments on a floor of the plant, that make up a single SBR basin.

For S**econdary treatment**, which to provide the final effluent quality described above was based on the CASS™ sequencing batch reactor process. The plant design was based on four basins. Owing to the limitations of site area availability, the basins are stacked one basin per floor in a four-storied configuration. Each basin was subdivided into six identical compartments, each 60 m long, 17.5 m wide and with a maximum depth to TWL of 4.7 m. Each compartment had a 16.5 m long decanter. Fully treated effluent was discharged via decanters and then flows to the Chao Phraya River through drop shafts, culverts and a final effluent cascade which ensures compliance with the minimum final effluent dissolved oxygen concentration.

For **Sludge treatment** and odor controlled, wasted activated sludge (WAS) was removed periodically from the SBR compartments by dedicated WAS pumps working under PLC control. One small submersible centrifugal pump was provided for this duty per compartment. Sludge was dewatered to minimum 20% dry solids content by means of stacked belt thickener/belt press units with a single stage of polymer dosing upstream. Sludge stabilization was done by dosing with slaked lime powder. Foul air from anticipated sources of odor was collected by a system of ductwork and transferred to a chemical scrubbing system by a system of fans.

2.1.2 CASS^{TM} process

Secondary treatment in Chongnonsi Wastewater Treatment Plant is based on an SBR process variant CASS™ (or Cyclic Activated Sludge System), which provides biological nutrient removal and is configured with an internal selector to controlled filamentous sludge bulking. A process cycle with aeration and non-aeration phases was used to provide aerobic, anoxic and anaerobic process conditions, which combined with aeration intensity, achieve nitrification, denitrification and biological phosphorus removal where required. Eight process cycles per day were operated, which each of 3-hour cycle time comprises of three periods, i.e.

1) Fill-Aerate for 75 min
2) Fill-Settle for 60 min
3) Decant for 45 min.
4) Idle for 15 min.

The CASS™ process combined plug flow initial reaction conditions with a complete mix reactor configuration. Each reactor compartment was divided by baffle walls into three zones, i.e. zone 1 with the area about 5% of the compartment worked as a selector (anaerobic or occasionally anoxic), zone 2 with the area about 10% of the compartment worked as an aerobic phase in 'Fill-Aerate' period or anoxic-anaerobic phase during 'Fill-Settle' period, and zone 3 with the area of 85% worked as aerobic, anoxic and anaerobic phases similarly to zone 2, as illustrated in Figure 2.1.4.

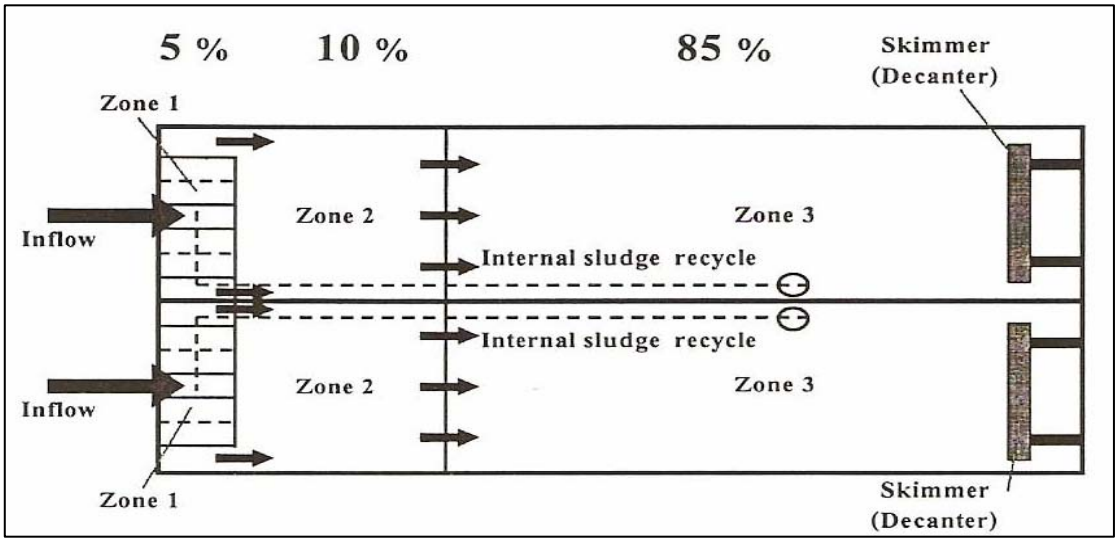


Figure 2.1.4 Cyclic Activated Sludge System (CASS) in Chongnonsi Wastewater Treatment Plant

Return activated sludge (RAS) was continuously recycled from zone 3 to zone 1 to maintain the initial reaction conditions to removed readily degradable soluble BOD in the influent and encourage the growth of floc-forming organisms. One small submersible centrifugal pump was provided for this duty per compartment. The flow of RAS was determined only by the design loading rate in terms of kg influent BOD

per kg of mixed liquor in the RAS and hence was much less than the flow of RAS in a conventional activated sludge plant.

The complete mix nature of the reactor, particularly in zone 3, provided flow and load balancing and a tolerance to shock or toxic loadings. During normal operation, each compartment was isolated from the inflow during decant, which helped prevented mixed liquor suspended solids washout during peak or wet weather hydraulic surges. The process configuration of other BPR plant as illustrated in Appendix F)

For treating typical domestic wastewater influent concentrations, this constituted a four hour cycle which is then repeated. As with any sequencing batch process, varying the duration of the cycle phases offered considerable flexibility in terms of being able to adapt the process to suit changing influent conditions. Nitrification and denitrification can be achieved simultaneously by controlling the aeration intensity during the aerobic period to ensured anoxic conditions within the activated sludge flocs in which dissolved oxygen penetration is limited, with ammonia oxidation taking placed externally to the flocs. The conditions within zone 1 of each compartment also provided polishing denitrification, as well as rapid enzymatic transfered of influent soluble substrate as part of enhanced biological phosphorus removal.

2.2 Phosphorus Cycle

Phosphorus was an essential nutrient for plants and animals in the form of ions PO_4^{3-} and HPO_4^{2-}. It is a part of DNA-molecules, of molecules that store energy (ATP and ADP) and of fats of cell membranes. Phosphorus was also a building block of certain parts of the human and animal body, such as the bones and teeth.

Phosphorus can be found on earth in water, soil and sediments. Unlike the compounds of other matter cycles phosphorus cannot be found in air in the gaseous state. This was because phosphorus was usually liquid at normal temperatures and pressures. It is mainly cycling through water, soil and sediments. In the atmosphere, phosphorus can mainly be found as very small dust particles. Phosphorus moved

slowly from deposits on land and in sediments, to living organisms, and than much more slowly backed into the soil and water sediment. The phosphorus cycle was the slowest one of the matter cycles that was described here. Phosphorus was most commonly found in rock formations and ocean sediments as phosphate salts. Phosphate salts that are released from rocks thronged weathering usually dissolves in soil water and would be absorbed by plants. Because the quantities of phosphorus in soil are generally small, it was often the limiting factor for plant growth. That was why humans often applied phosphate fertilizers on farmland. Phosphates were also limiting factors for plant-growth in marine ecosystems, because they were not very water-soluble. Animals absorbed phosphates by ate plants. Phosphorus cycles through plants and animals much faster than it did through rocks and sediments. When animals and plants died, phosphates would return to the soils or oceans again during decay. After that, phosphorus would end up in sediments or rock formations again, remaining there for millions of years. Eventually, phosphorus was released through weathering, as illustrated in Figure 2.2.1.

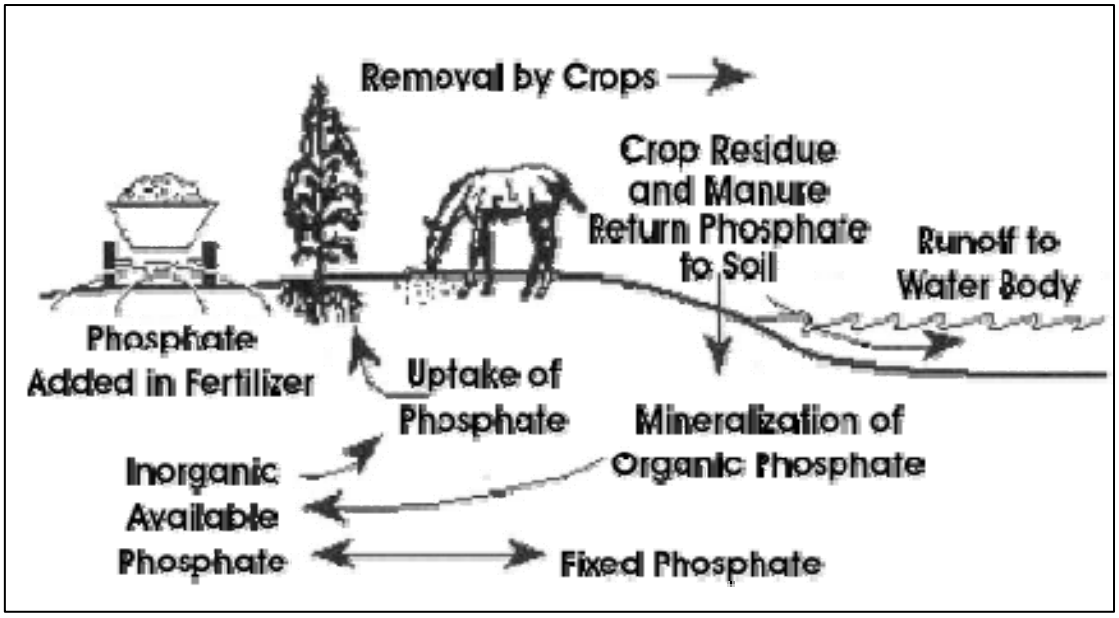


Figure 2.2.1 Phosphorus Cycle (Busman, 1997)

2.3 Phosphorus and water quality

Phosphorus was one of the key elements necessary for growth of plants and animals. Phosphates PO_4^{3-} were formed from this element. Phosphates existed in three forms: orthophosphate, polyphosphate (or metaphosphate) and organically bound phosphate. Each compound contains phosphorous in a different chemical formula. Ortho forms were produced by natural processes and were mostly found in sewage. Poly forms were used for treating boiler waters and in detergents. In water, they change into the ortho form. Organic phosphates were important in nature. Their occurrence may result from the breakdown of organic pesticides which contained phosphates. They may exist in solution, as particles, lost fragments or in the bodies of aquatic organisms.

Environmental Impact the rainfall could cause varying amounts of phosphates to wash from farm soils into nearby waterways. Phosphate would stimulate the growth of plankton and aquatic plants which provided food for fish. This may caused an increased in the fish population and improved the overall water quality. However, if an excess of phosphate entered the waterway, algae and aquatic plants would grow wildly, choked up the waterway and used up large amounts of oxygen. This condition was known as eutrophication or over-fertilization of receiving waters. This rapid growth of aquatic vegetation eventually died and as it decays it used up oxygen. This process in turn caused the death of aquatic life because of the lowering of dissolved oxygen levels.

2.4 Biological phosphorus removal

Eutrophication had become one of the most important and worldwide water quality problems. Phosphorus removal from sewage and industrial wastewater had been considered as a key strategy in preventing eutrophication. Enhanced biological phosphorus removal (EBPR), an economical and sustainable method of phosphorus removal, was being widely adopted in many wastewater treatment plants. EBPR was characterized by circulation of activated sludge between anaerobic and aerobic conditions (Seviour et al., 2003).

The theory of luxury uptake of phosphorus was now well developed (Wentzel et al. 1990; Wentzel et al. 1991). It had been shown that exposing the mixed liquor to an anaerobic/aerobic sequence in the biological reactor selects microorganisms that accumulated higher levels of intracellular phosphorus than other microorganisms. Phosphorus-removing microorganisms were able to rapidly assimilate and stored volatile fatty acids (VFAs) and other fermentation products under anaerobic conditions. Phosphorus was released in the anaerobic zone to produce the energy needed to take up the fermentation products, which were stored as poly-ß-hydroxybutyrate. Phosphorus-removing microorganisms produce energy by oxidizing the stored fermentation products in the aerobic zone while simultaneously accumulating intracellular phosphate. The ability of phosphorus-removing microorganisms to rapidly assimilate the fermentation products under anaerobic conditions gave them a competitive advantage over other microorganisms and results in their preferential growth in the wastewater treatment system. Thus, the anaerobic-aerobic sequence allows the selection of a large population of phosphorus-removing microorganisms.

In BPR systems, phosphorus accumulated in the biomass and was removed in the form of waste-activated sludge. A recent study showed that nearly all the enhanced phosphorus removal was due to the storage of polyphosphates. This resulted in an increased in the inorganic sludge mass but no significant increased in organic sludge production when compared to a conventional activated sludge process without chemical addition (Jardin and Popel 1995). Chemical precipitation of phosphorus had been estimated to increase sludge production by an average of 26% (Sedlak 1991).

Several process configurations (some patented, others not) were currently being applied worldwide for biological phosphorus removal. Some process configurations incorporated nitrogen removal by nitrification and denitrification along with biological phosphorus removal. However, all were based on the sequential exposure of microorganisms to anaerobic and aerobic conditions in the biological reactor.

2.5 Phosphorus removal under anaerobic and aerobic condition

If a suspended growth bioreactor system is configured as two zones in series with the firth zone is anaerobic condition and the second is the aerobic condition. The PAOs that process a special metabolic capability not commonly found in other bacteria. It will proliferate and store large quantities of inorganic phosphate as polyphosphate. Thereby, allowing phosphorus removal from wastewater via biomass wastage.

2.5.1 Phosphorus removal under anaerobic condition

Under anaerobic condition, the capability of heterotrophic microorganisms to metabolized organic matter was dramatically reduced, since no terminal electron acceptor was available. Organic matter cannot be oxidized to generate energy. Fermentative reactions could occur, but these reactions resulted in only limited production of energy for growth and other purposes by the microorganisms. In contrast, the phosphorus accumulating microorganisms were able to transport soluble organic matter acrossed the cell membrane and stored in the form of high-energy bonds.

Acetate and other fermentation products such as volatile fatty acids (VFAs) were produced from fermentation reaction by the facultative organisms. The fermentation products were preferred and readily assimilated and stored as poly-B-hydroxyburates (PHBs) by the microorganisms capable of excess biological phosphorus removal. This assimilation and storage were aided by the energy made available from the hydrolysis of the stored polyphosphate provided energy for active transport of substrate and for formation of acetoacetate, which is converted to PHB.

In general, microorganisms responsible for EBPR such as polyphosphate accumulating organisms (PAOs) were capable of storing organic compounds, such as short chain fatty acids (SCFA) as internal storage compounds (poly-3-hydoxyalkanoates; PHA). Energy and reducing power for PHA storaged generate respectively from the degradation of polyphosphate and glycogen under anaerobic

conditions. Therefore, phosphate was released during anaerobic condition while short chain fatty acids were being assimilated into cells.

2.5.2 Phosphorus removal under aerobic / anoxic condition

Under aerobic conditions, the PAOs used the stored PHA to produced energy for cell growth and maintenance as well as orthophosphate uptake from bulk liquid to build up polyphosphate. It occurred without the presence of external carbon substrates. The net phosphorus removal could be achieved by wasting excess sludge of high P content because the aerobic phosphorus uptake was greater than the anaerobic phosphorus released, as illustrated in Figure 2.5.1.

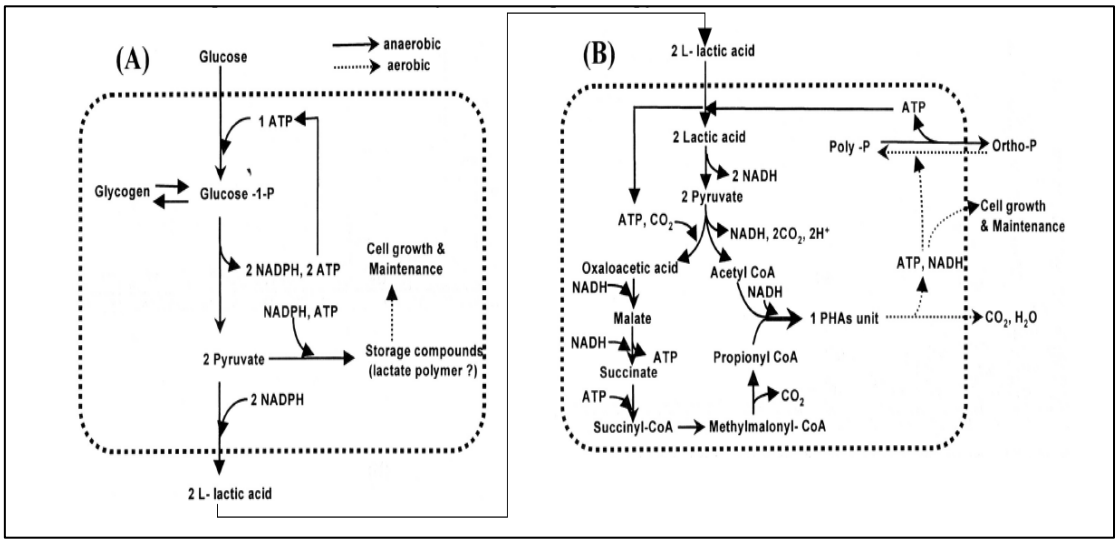


Figure 2.5.1 Proposed metabolic pathways for conversion of glucose to lactate polymer by LPO (part A) and for conversion of lactate to PHAs and phosphorus removal by PAO (part B) (Jeon and Park, 2000).

Initially, little attention was paid to the reactions occurring in the anaerobic phase and aerobic uptake was thought to occur because of stress caused to the organisms due to the different stages the system was operated in. As such, nearly all attention was initially focused on aerobic reactions and optimization of that phase. This had its implications on microbial research, where emphasis was put on micro-

organisms capable of high aerobic phosphorus uptake. Considerably more insight has now been gained in the metabolisms underlying the EBPR process. Currently the existence of pure biological phosphorus is proven, but -depending on concentration levels of other constituents - partial chemical precipitation and/or adsorption processes can occur simultaneously. The most important disadvantage of EBPR concerns the reversible nature of biological phosphate storage. Thus, the organisms can breakdown the internal phosphorus content and release it again to the environment. Careful handling of the sludge is necessary. Sludge retention times in the settler should be limited and the oxygen supply to the aerobic phase should provide sufficient oxygen also to the outlet of the basin to prevent anaerobic conditions occurring in the secondary clarifier (Reddy, 1998). Release of phosphorus can, however, is turned to advantage when coupled with chemical phosphorus recovery processes. The important advantages of EBPR are low sludge production and the fertilizer value of the sludge. Difficulties in assuring stable and reliable operation unfortunately still are reported.

2.5.3 The P release/uptake phenomenon in activated sludge systems

The rapid removal of nitrates from solution in wastewaters is governed to a large extent by the concentration and the type of biodegradable organic carbon substrate that was made available to the denitrifying bacteria. The phosphorus removing bacteria in wastewater systems also rapidly take up readily biodegradable organic carbon substrates. Thus, the phosphorus removing bacteria and denitrifiers would be competed for the available readily biodegradable organic carbon present. If complete denitrification was the primary purpose of the wastewater treatment system, then the presence of phosphorus removing bacteria can have a major impact on removal rates. The following sub-section would briefly discuss the process of biological phosphorus removal in activated sludge systems. The biologically enriched phosphorus removal has been well documented (Wentzel *et al*., 1985 ; Wentzel *et al*.,1989a ; Wentzel *et al*., 1989b and Wentzel *et al*., 1992 ; Kerrn-Jespersen and Henze, 1993 ; Mino *et al*., 1998 ; Brdjanovic *et al*., 1998a,b,c,d ; Meinhold *et al*., 1999). The biological phosphorus removal from wastewater can be achieved by

stoichiometric coupling to microbial growth or enhanced storage in the biomass as polyphosphate (Van Loosdrecht *et al*., 1997b). In the anaerobic phase, the biological phosphorus removing bacteria take up carbon sources (short chained fatty acids) and store them in the form polyhydroxyalkanoates (PHA). The energy required is generated by the conversion of glycogen and polyphosphate. The degradation of polyphosphate results in its release into the bulk solution (Figure 2.5.2). In the subsequent aerobic or anoxic phase the internal pool of polyhydroxyalkanoates is oxidized and used for growth, phosphate uptake, glycogen synthesis and maintenance (Van Loosdrecht *et al*., 1997a ; Brdjanovic *et al*., 1998a). Thus, in an enhanced biological phosphorus removal (EBPR) system, the behavior of the 3 storage pools viz: PHA, poly-P, and glycogen, in cells is highly dynamic and is determined by their conversion during the anaerobic and aerobic (or anoxic) phase (Brdjanovic *et al*., 1998b), as illustrated in Figure 2.5.3.

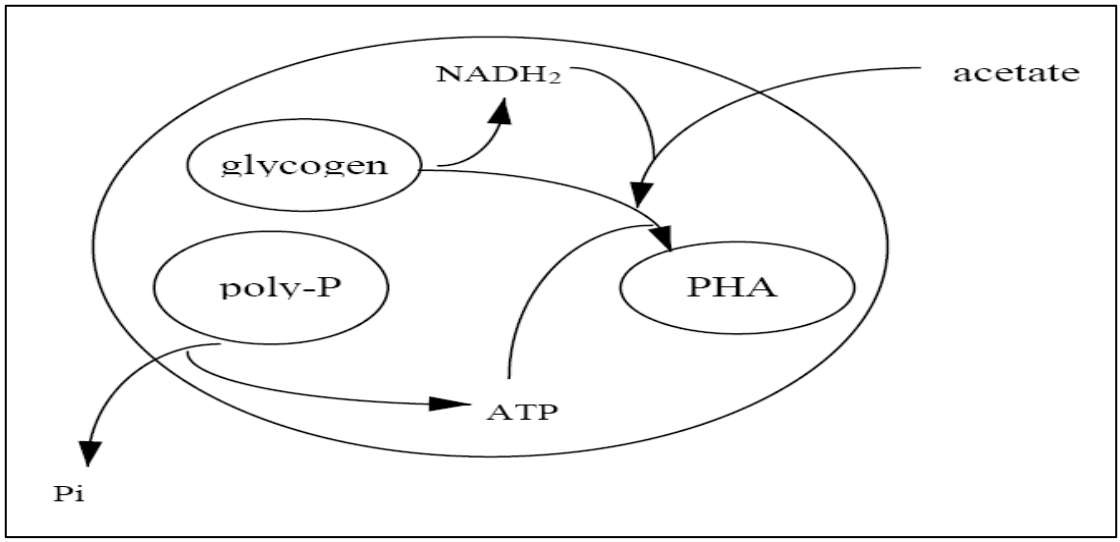


Figure 2.5.2 Metabolic processes of polyphosphate accumulating organisms involved in anaerobic phase of phosphorus removal systems (poly-P - polyphosphate ; PHA - polyhydroxyalkanoate) (from Van Loosdrecht et al., 1997).

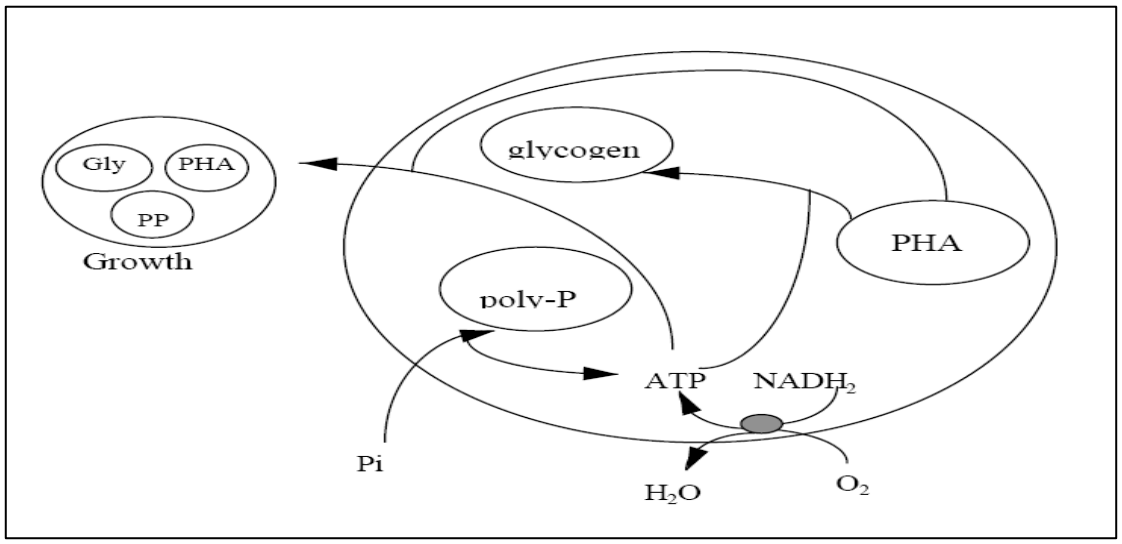


Figure 2.5.3 Metabolic processes of poluphosphate accumulating organisms involved in anaerobic/aerobic phosphorus removal (Gly - glycogen; PP - polyphosphate; PHA - polyhydroxyalkanote) (from Van Loosdrecht et al., 1997).

2.6 Poly – P Bacteria

Under the anaerobic conditions energy was required for transport of external substrates into the cell, conversion of substrates to PHA, which related metabolism, and maintenance. Poly-P was considered to be the energy storage polymer for anaerobic substrate uptake. As mentioned previously, during the anaerobic phase short chained fatty acids were taken up by the bacterial cells with a concomitant release of phosphorus into the bulk liquid, as illustrated in Figure 2.6.1. The appearance of phosphorus in the bulk liquid is as a result of the degradation of internal reserves of polyphosphates to provide the energy necessary for production of storage compounds like polyhydroxyalkanoates. However, phosphorus release in the aerobic zone could lead to deterioration in overall efficiency of the EBPR system (Brdjanovic *et al*., (1998b). The cells internal the poly-P supplies were replenished during the aerobic phase by the phosphorus uptake from the bulk liquid (Sorm et al., 1997 ; Mino et al., 1998).

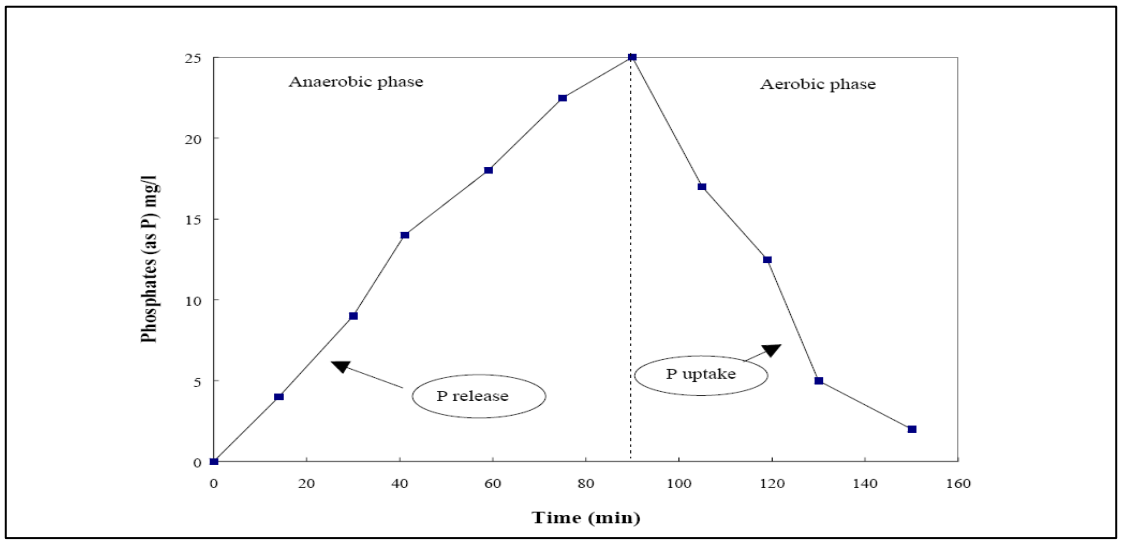


Figure 2.6.1 The course of ortho-phosphate concentration under anaerobic and aerobic conditions during experiments using the Dephanox process (adapted from Sorm et al., 1997).

It has been shown that the enzyme, AMP- phospho transferase, catalyzes the reaction following:

(Pi) n + AMP → (Pi) n-1 + ADP.

This enzyme appeared to be responsible for the energy conservation in bacteria which were capable of phosphorus removal. One of the strange phenomena observed in enhanced biological phosphorus removal systems was the variation in the ratio of carbon source taken up to phosphorus released. It has been reported that a lower pH gave a lower P-release/acetate uptake ratio with a variation of 0.25 to 0.75 P-mol/C-mol (Mino et al., 1998). Brdjanovic *et al*. (1997a) further suggested that the energy source) would be limiting at high pH since more energy is required for acetate transport through the membrane at high pH. Moreover, this variation indicated that the dependency on poly-P as energy source could vary due to the balance between production and consumption of energy in the cell. The energy requirements for the PHA formation metabolism depends on the metabolic pathways used (Mino *et al*., 1998).

It was shown that excessive aeration leads to a quick full depletion of the already relatively low PHA content of the bio-P cells present at the end of the standard

aerobic phase. After the system was returned to normal operation the phosphorus uptake was strongly affected due to the dependence of phosphorus uptake on the PHA content of the bacterial cells. The aerobic phosphorus uptake depended not only on the polyhydroxyalkanoate concentration but also on polyphosphate content of the cells. Under aerobic starvation conditions glycogen cannot replace PHA's for phosphorus uptake and was only used for maintenance. During this period no oxygen consumption due to decay processes has been observed (Brdjanovic *et al*., 1998b). Since the phosphorus release was hardly affected, the net result was decreased phosphorus removal efficiency after a period of excessive aeration.

The bacteria involved in the bio-P process have a complex physiology, in which the formation and degradation of polymers (such as polyphosphate) and carbon compounds (such as glycogen and polyhydroxyalkanoates). Poly-P organism stored the phosphate in the form of poly-P for maintenance purpose.

The phosphorus may be 1-3% of the dry weight of a bacterium (Michael H. Gerardi, 2006). Phosphorus exists in inorganic forms. Inorganic forms of phosphorus include orthophosphates and polyphosphates are available for biological metabolism without further breakdown and are considered to be the readily available nutrients for phosphorus for bacterial use in wastewater treatment plants and aquatic plants in natural waters.

2.7 Polyhydroxyalkanoates (PHAs)

PHAs make up a class of polymers that were fully biodegradable. They were a family of polyesters with a wide array of physical properties that can range from stiff-brittle plastics to elastomers and to rubbers. PHAs were naturally produced in numerous genera of bacteria, and have been amplified through bacterial fermentation. PHAs were mainly composed of R-(-)-3-hydroxyalkanoic acid monomers. There could be broadly subdivided into two groups as shown in Figure 2.7.1.

Short chain length PHAs

- consist of 3 carbon - 5 carbon monomers (C3-C5)
- produced by bacterium *Alcaligenes eutrophus* (plus others)

Long chain length PHAs

- consisted of 6 carbon - 14 carbon monomers (C6-C14)
- produced by *Pseudomonas oleovorans* (plus others)

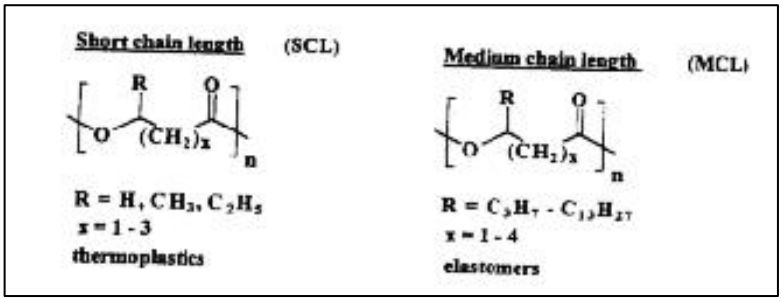


Figure 2.7.1 Short chain and long chain length of polyhydroxyalkanoate (PHAs) **(**Kumar and Minocha, 1999**)**

Each type of PHA generally consisted of 1000-10000 monomers, but most were synthesized by short chain length monomers. There are many different typed of PHAs, distinctly characterized by chain length, type of functional group and degree of unsaturated bonds (Figure 2.7.2). A higher degree of unsaturated bonds increased the rubber qualities of a polymer, and different functional groups changed the physical and chemical properties of a polymer.

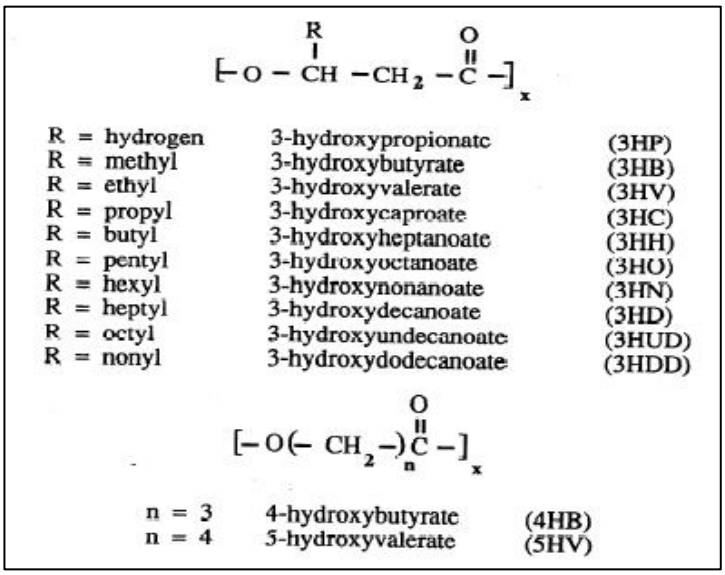


Figure 2.7.2 molecular structures of various PHAs (Kumar and Minocha, 1999).

PHB (or P (3HB)) was the most common type of PHA produced and was an example of a short chain length homopolymer produced by *A. eutrophus*. PHB had poor physical properties for commercial used as it is stiff, brittle, and hard to process. This had led to an increased interest to produce heteropolymer with improved qualities. P (3HB-3HV) is an example of an improved heteropolymer. It was commercially named as BIOPOL™, and was produced at the time by Zeneca company, which currently owned by Monsanto. Compared to PHB, P (3HB-3HV) was less stiff, tougher, and easier to process, making it more suitable for commercial production. It was also water resistant and impermeable to oxygen, increasing its value.

Initially, polyhydroxybutyrate (PHB) was recognized as the storage polymer in the anaerobic phase (Clayton et al., 1991; Wentzel et al., 1995). It was later verified that the PHB-like polymer contains 3-hydroxybutyrate (3HB) and 3-hydroxyvalerate (3HV) as monomeric building units. These polymers are now referred to as polyhydroxy-alkanoates (PHA) in general. Polyhydroxyalkanoates have been verified to be co-polymers composed of these 4 units. When acetate is the sole substrate, then 3HB is the major unit in the PHA formed (Barker and Dold, 1997; Shuler and Jenkins, 1997; Mino et al., 1998). Polyhydroxyalkanoate is a more reduced compound than acetate, therefore the conversion of acetate, a favourable substrate for enhanced

biological phosphorus removal, to PHA requires reducing power. Two possibilities exist for the generation of this reducing power in bacterial cells. In the Comeau-Wentzel model it is suggested that the required reducing power is produced by partial oxidation of acetyl Co-A through the tricarboxylic acid cycle. In the Mino model the reducing power is considered to be derived from degradation of intracellularly stored glycogen (Satoh et al., 1992; Van Loosdrecht et al., 1997a; Mino et al., 1998).

However, it is also likely that there may be a partial functioning of the tricarboxylic acid cycle. Bordacs and Chiesa (1989) and Pereira et al., (1996) found that a small fraction of the carbon in acetate was released as CO_2. Based on redox balance considerations, Pereira et al., (1996) concluded that the reducing power generated in the observed degradation of glycogen was insufficient to account for the polyhydroxyalkanoate production. These are strong indications that a small fraction of acetate is metabolized through the tricarboxylic acid cycle under anaerobic conditions supplying a minor part of the reducing power for polyhydroxyalkanoate formation. The anaerobic polyhydroxyalkanoate production is dependent on substrate loading while the aerobic polyhydroxyalkanoate consumption depends on the PHA level inside the biomass. The polyhydroxyalkanoates that are not used will accumulate in the cell until a saturation level is reached. Once this level is reached no further acetate uptake will occur under anaerobic conditions (Brdjanovic et al., 1998d; Meinhold et al., 1999).

In biological phosphorus removal systems the aerobic solids retention time (SRT) should be long enough to oxidize the amount of polyhydroxyalkanoate stored in the cell during the anaerobic phase. Thus, the minimally required solids retention time depends on the polyhydroxyalkanoate conversion kinetics and the cell PHA storage capacity. It was also shown that the PHA consumption was strongly influenced by temperature during long term experiments i.e. microorganisms exposed to a change in temperature for a relatively long time. It was concluded that temperature effect on the stoichiometry and phosphorus uptake process rate. However, a strong temperature effect on the metabolic processes such as PHA consumption and growth was observed i.e. it was observed that the conversion rate of storage polymers decreased with a decrease in temperature (Brdjanovic et al., 1998c).

PHB was 100% biodegradable. Various bacteria and fungi degrade PHB to carbon dioxide and water through secreting enzymes. It could be also degraded through non-enzymatic hydrolysis. The fastest degradation appeared under conditions of high temperatures and mechanical disruption. An 80% loss of PHB had been degraded in 15 weeks. PHB was also biocompatible, meaning it was a metabolite normally present in blood.

Researchers had amplified the production of PHAs for large scale production, to produce and commercialize biodegradable plastics. Originally bacterial fermentation was used, but PHAs could only be produced on a small scale this way, and production costs were to expensive compared to production of conventional plastics. Researchers had since tried large scale production through transgenic plants, but many problems have arisen this way also. More research must be done before commercial production of PHAs will be able to out compete or replace conventional plastics.

2.8 Biochemical Models of EBPR Metabolism

Several mechanisms have been proposed to explain the enhanced uptake of phosphorus by microorganisms in wastewater. It has been shown that for biological phosphorus removal to occur in wastewater treatment plants, biomass first needs to pass through an oxygen and nitrate free phase, i.e. an anaerobic phase, before entering a phase where an electron acceptor is present, i.e. an anoxic phase where nitrate is present or an aerobic phase where oxygen is present (References see sections below). The oxygen and nitrate free phase can be achieved in a separate reactor, the first section of a plug flow reactor or part of a sequencing batch reactor cycle. Figure 2.8.1 presents the concentration profiles of the mean measurable components for EBPR operated under anaerobic-aerobic conditions.

The main forms of these PHAs are Poly-beta-HydroxyButyrate (PHB) and Poly-beta-HydroxyValerate (PHV). The energy to store this polymer is obtained from breakdown of glycogen and hydrolysis of energy rich internal phosphorus chain called poly-Phosphate (poly-P). Since poly-P was broken down to ortho-phosphate for

energy supply, the phosphate concentration in the anaerobic phase increases. The anaerobic phase needs to be followed by an oxygen or nitrate rich phase, i.e. an anoxic phase (anoxic P-removal) or an aerobic phase (aerobic P-removal). During this phase the stored PHB was consumed, generating energy for growth, for uptake of ortho-phosphate from the liquid phase and generating energy and carbon for replenishment of the glycogen and poly-P pools.

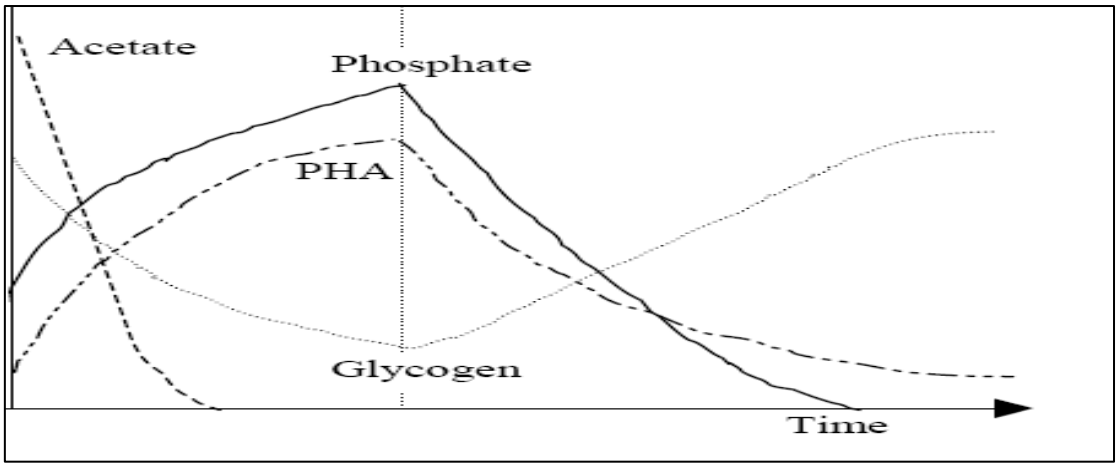


Figure 2.8.1 Schematic representation of concentration profiles for EBPR under anaerobic aerobic conditions (Ref)

The major EBPR models, and significant additions to them, were given below in chronological order of their development, with brief explanations:

Comeau-Wentzel Model (1986): PHAs was a reduced energy source and its synthesis therefore requires reducing powers. Partial oxidation of acetyl Co-A through the TCA cycle produces the reducing power. The combination of acetate and reducing power produce PHA. The proposed stoichiometry of the EBPR process was given by Comeau-Wentzel in Figure 2.8.2 (a).

Mino Model (Mino et al., 1987): The lacked of evidence for the operation of the TCA cycle under anaerobic conditions and the observation of significant changes in intracellular carbohydrate (glycogen) content motivated the development of the Mino model (1987). In this model, reducing power was generated by the degradation of intracellular stored glycogen (carbohydrate) via the Embden-Meyerhoff Parnas

(EMP) pathway. The stoichiometry of the proposed model was also given in Figure 2.8.2 (b).

Modified Mino Model (Wentzel, 1991): The only major change from the Mino model was that the modified Mino model postulates the Entner-Doudoroff (ED) pathway for degradation of intracellular glycogen instead of the EMP pathway. This modification was proposed by Wentzel (1991) based upon the 7 results of a single studied in which the apparent used of the ED pathway by an *Acinetobacter* was observed.

Pereira et al. (1996): The authors showed that a small portion of labeled acetated was released as CO_2 during an anaerobic batch test experiment. Therefore, their 13C NMR resulted suggest that at least part of the TCA cycle was still operable under anaerobic conditions, and that some fraction of the reducing power needed was generated through the TCA cycle. The complete pathway of the model was illustrated in Figure 2.8.3.

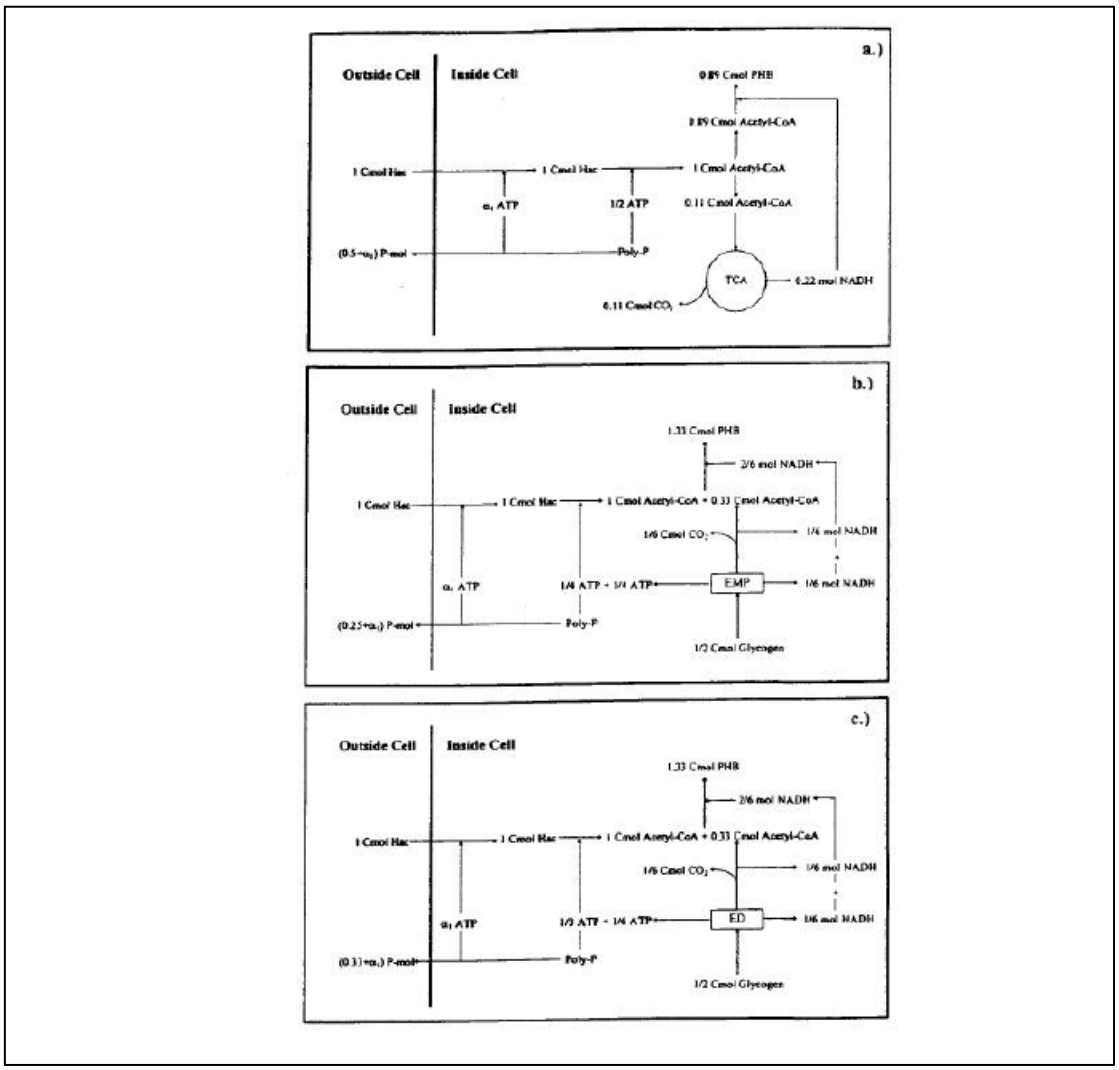


Figure 2.8.2 a) Comeau-Wentzel, b) Mino and c) Modified Mino models

Maurer et al. (1997): The authors used a solid state NMR to track carbon flow in EBPR sludge fed with domestic sewage. Although no suggestion was made about the operation of the TCA cycle under anaerobic conditions, they suggested that the ED pathway was used during glycogen breakdown.

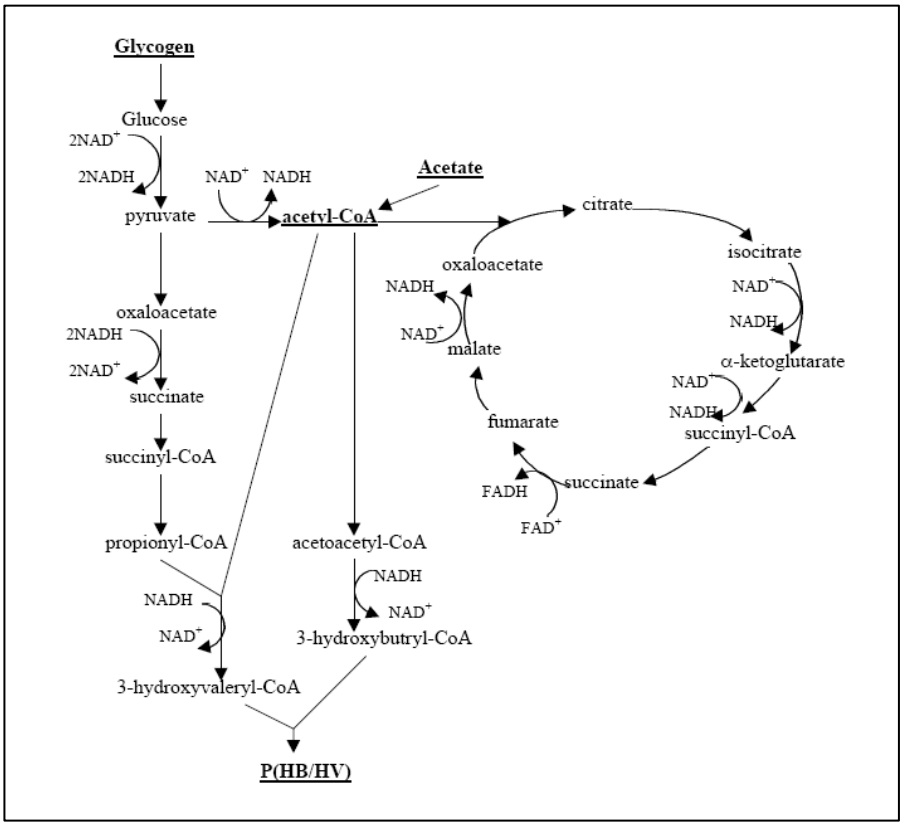


Figure 2.8.3 EBPR model proposed by Pereira et al. (1996).

Louie et al. (2000): The authors suggested that the glyoxylate pathway is active under anaerobic conditions to provide reducing equivalents and to maintain stable NAD+/NADH balance.

It was obvious that all of the biochemical pathways of EBPR were not completely defined as yet. In addition to unknown biochemical mechanisms, the effects of other factors that affect the performance of EBPR processes were incompletely understood, notably temperature. Conflicting reported concerning the effected of temperature upon EBPR processes had repeatedly appeared in the research literature over the last two decades. The diverse bacterial consortium responsible for the EBPR processes in biological wastewater treatment systems consist of psychrophilic, pyschrotrophic and mesophilic heterotrophic bacteria. Because they had different optimum growth temperatures, the temperature of the wastewater-microbial mixture (mixed liquor) strongly influences the population composition of the consortium. Temperature was also a key parameter that affected the performance of the microbial consortium. Two major effected were exerted by temperature. It

influences the rates of enzymatically catalyzed reactions and affected the rate of diffusion of substrate into the cells (Grady et al., 1999). Substantial research efforts had been made to more fully define temperature affected on the kinetics and performance of EBPR systems during the last two decades.

Sell (1981), Kang et al. (1982), Ekama, et al. (1984), Siebrietz (1984) and Barnard et al. (1985) reported that EBPR efficiency was greater at lower temperatures than at higher temperatures where investigated temperatures ranged from 5 to 24^{o}C.

McClintock et al. (1991) measured the performance of an EBPR system at 20, 15 and 10^{o}C and reported that EBPR functions would "wash-out" of activated sludge systems at 10^{o}C before heterotrophic COD removal functions.

Mamais and Jenkins (1992) showed the early wash-out of EBPR functions at several combinations of temperature and SRT.

In recent studies, **John and Stephenson (1996), Brdjanovic, et al. (1997; 1998), Choi (1998) and Beatons et al. (1999)** had shown that EBPR reaction rates became slower with decreasing temperature, as was typical of biochemical reactions. Although temperature appeared to affect EBPR reaction rates in a normal manner, a substantial body of evidence indicates that many EBPR systems perform more efficiently as the temperature decreased.

Helmer and Kunst (1997) have speculated that PAOs were more psychrophilic than competing heterotrophs, and this gave them a competitive advantage at low temperatures, resulting in a population shift towards PAOs and greater P removal efficiency in spite of the decreasing reaction rates. Similar observations supporting better EBPR removal at cold temperature were made by Panswad et al. (2000; 2003). Although the resulted of temperature effects on EBPR kinetic rates are similar, research findings show considerable disagreement about the performance of the EBPR systems under different temperature conditions.

2.9 Factors associated with the Bio-P process

In this section, external factors influencing the EBPR process will be discussed. Whereas initial research mainly focused on the aerobic processes it became gradually clear that good phosphorus removal activity can only be obtained when anaerobic micro-organisms are subjected to conditions favoring storage of sufficient carbon sources, to be utilized under aerobic conditions with simultaneous uptake of orthophosphate. This section comprises external factors that directly influence the anaerobic process and thus indirectly the overall process. First, attention will be focused on the carbon sources utilized by the responsible microorganisms, and how these carbon sources influence the phosphorus release, the formation of PHAs and the influence on the overall EBPR performance. These paragraphs are followed by a paragraph on possible proliferation of non-PAOs under anaerobic conditions and their influence on the EBPR process. This section follows the carbon sources, since the latter will reveal predominantly responsible for proliferation of non-PAOs competing for the same substrate as PAOs. Other factors mentioned in literature that can temperature, pH, influence the EBPR performance are external, Nitrate/Oxygen**,** , presence of nitrite sludge loading/age and SRT. These factors would be discussed in separate sections.

2.9.1 Temperature

Temperature constitutes a complex factor in the Bio-P process (Janssen et al, 2002; Tykesson, 2005). According to the temperature effect on the activated sludge process, it also affected the EBPR process. Nakamura et al. (1995) studied the effect of temperature on phosphate release and uptake using the polyphosphate-accumulating bacteria, *Microlunatus phosphovorus* and strain NM-1. The highest rate of phosphorus release was observed at 25°C in comparison to those at 5°C and 35°C. The phosphorus uptake rate was higher at 15 and 25°C, while the lower rate was observed at 5 and 35°C. McClintock (1990) reported that cold temperatures have an adverse effect on EBPR processes. He observed EBPR washout at a 5 day MCRT at 10°C. He also stated that temperature had a greater impact on nitrification and denitrification rates when the system was operated at lower MCRTs. According to Brooks (1996),

Sedlak (1991), Vinconneau and coworker (1985), Sell and coworker (1981) and von Consbruch (1995) reported that higher phosphorus removal efficiency was obtained at colder temperature. Janssen et al (2002) reported that some temperature effected on the activated sludge as follows: changes in physical/chemical processes such as precipitation, changes in the conditions of organisms such as the activity of PAOs, changes in sludge populations, such as the fraction of PAOs in the sludge. It was generally understood that the net change in temperature can positive or negative affected the Bio-P process efficiency. For example, nitrification and the production of VFA were both important and dependent on the temperature (Tykesson, 2005). Moreover, the competition between the PAOs and the GAOs was dependent on temperature. At higher temperatures, GAOs had been found more than the PAOs. The EBPR process has been known to perform better at colder temperatures (5-20^{o}C) (Tykesson, 2005). In a study carried out by Marklund and Morling (1994) in the north of Sweden, it had been found that it was possible to maintain a Bio-P process down to a water temperature of 4^{o}C and 5^{o}C (Tykesson, 2005).

2.9.2 pH

The pH of the activated sludge process affects the Bio-P process. This was more important in the anaerobic phase where the VFA uptake rate for GAOs was affected. Studied have shown that the GAOs take up acetate faster at lower pH. This by implication means that the PAOs were more competitive at higher pH. Hence, higher pH- values could improve the performance of the EBPR process (Tykesson, 2005). In a similar way, it was found out that low pH seems to be beneficial for the GAOs in the aerobic zone. While the GAOs were relatively insensitive to lower pH, the rates of phosphate uptake and PHA degradation for PAOs were strongly affected. These conclusions had been drawn from laboratory sequence batch reactor-studied with acetate as the carbon source. The results were probably transferable to a full-scale continuous system with real complex wastewater. Studied performed by Tracy and Flammino (1985) have shown that EBPR mechanisms do not function at less than pH 5.4. According to Reddy (1998) studies have not been performed to evaluate the effect of high pH-values on the EBPR process. However, the author stated that it was known that the EBPR mechanism can operate in the pH-range 8.5 to 9, but chemical

precipitation also becomes important. In the following paragraphs the influence of the external pH on the anaerobic and the aerobic reactions and on the overall EBPR process is elaborated. However, in literature not very many reports could be found described that the influence of pH on the EBPR process, limiting the number of references used.

2.9.3 Influent composition

The composition of the influent wastewater that had to treated by the Bio-P process was important in determining the efficiency of the process.

Counter ions: Potassium, magnesium and possibly calcium were involved in the Bio-P mechanism. Tykesson (2005) found out that the ratios between K and P were higher in batch tests with propionate than with acetate as the carbon sources. Different groups of bacteria can behave differently both regarding the carbon source and the counter ion. A lack of K and Mg had been reported to be detrimental for the EBPR-process and hence, these metals could be highly involved in the microbial competition. Readily degradable COD, Volatile fatty acids: The volatile fatty acids acetate, propionate and butyrate constitute the substrate for PAOs. Wastewater with a high composition of these compounds would certainly be more likely to be treated successfully by the Bio-P process. The fraction of VFA in wastewater, however, may be increased by fermentation (hydrolysis and acidogenesis) of the fermentable fraction of COD and partially from the slowly biodegradable COD fraction in the anaerobic phase. Fermentation of primary sludge also increases the fraction of VFA in wastewater. An increase in VFA concentration would definitely increase the selection of PAOs over the GAOs and thus, increased the possibility for the Bio-P process to take place affecting the performance of BNR systems. Ekama, et al. (1983) reported that wastewater characteristics, i.e., COD concentration, TKN:COD ratio, readily biodegradable COD concentration, maximum specific growth rate of nitrifiers, maximum and minimum temperatures, and P:COD concentration ratio, affect the design of a BNR process and control the effluent quality. They also reported that a biodegradable COD concentration of greater than 60 mg/L was need to achieve sufficient phosphorus removal, even with the absence of nitrates in the anaerobic zone. Siebritz, et al. (1983) suggested that at least 25 mg/L of biodegradable substrate

was required to stimulate anaerobic phosphorus release and subsequent phosphorus uptake in the aerobic zone. Gibson and Dold (1993) described the detailed characterization that was needed to accurately predict the performance of BNR processes using equations developed by Marais and co-workers at the University of Cape Town. However, Randall, et al. (1992) suggested that typically characterized influent wastewater could be used as a reasonable predictor for effluent nitrogen and phosphorus concentrations from BNR processes. The organic matter, i.e., BOD_5 and COD, to total phosphorus ratio entering the anaerobic zone will determine the effluent phosphorus concentration of the system. They compiled the data from full-scale and pilot-scale studied and develop graphs which suggest that a BOD_5:TP ratio of about 20:1 and COD/TP ratio of about 40:1 were needed to achieve effluent phosphorus concentrations of 1 mg/L or less for typical wastewater treatment plants. According to Randall, et al. (1992), Ekama and Marais (1984) reported that 8.6 mg/L COD is required to remove 1 mg/L nitrate while 50 to 59 mg/L COD is needed to remove 1 mg/L phosphorus from municipal wastewater. Experiments at Virginia Tech reported approximately 50 mg/L COD was required per mg/L phosphorus removed. Abu-ghararah and Randall (1991) studied the effect of influent organic compounds on the performance of the UCT process. They concluded that at least 20 mg acetic acid as COD was required to remove 1 mg of phosphorus.

2.9.4 Nitrate/Oxygen

Nitrate and oxygen can have positive affected on the Bio-P process since they are needed in the aerobic and anoxic zones to stored phosphate biologically within the activated sludge process. Nitrate and oxygen could have a negative affected on the Bio-P process if they enter the anaerobic tank through the influent and/or return sludge streams. If this happens, the PAOs would not be able to stored organic matter with energy obtained from the breakdown of polyphosphates in the anaerobic phase. At the same time readily degradable organic matter that could have been used by the PAOs would be decomposed using oxygen and nitrate as terminal electron acceptors and therefore would be unavailable for the PAOs.

Barnard (1983), Nicholls, et al. (1985) and Randall, et al. (1992) stated that the amount of DO or nitrates to the anaerobic zone should be minimized in order to obtain

high removal efficiencies of nitrogen and phosphorus. Organic matter otherwise available for poly-P bacteria will be oxidized when dissolved oxygen or nitrate is present in the anaerobic zone. Bacteria could obtained more energy for growth using these electron acceptors than storing organic matter as PHB. The presence of nitrate and dissolved oxygen results in lesser amounts of PHB storage and, therefore less energy available to the poly-P bacteria for uptake phosphorus under aerobic conditions. Likewise, the present of dissolved oxygen in the anoxic zone results in the denitrifying bacteria using dissolved oxygen preferentially instead of nitrates because they obtain more energy for growth, from dissolved oxygen. This, the total amount of denitrification in the anoxic zone will be reduced.

Iwema and Meunier (1985) conducted batch experiments and concluded that anaerobic phosphorus release decreased as the concentration of nitrate increased. The presence of nitrate or dissolved oxygen in the anaerobic zone, or the presence of dissolved oxygen in the anoxic zone will limit the performance of the BNR system. Nicholls et al. (1985) however stated that if influent wastewater contains sufficient VFA relative to the electron acceptor present, phosphorus removal will be achieved anyway.

Under aerobic conditions, sufficient dissolved oxygen transfer should be maintained for poly-P bacteria to take up phosphorus back into the cells and for obtaining good nitrification. If the aerobic dissolved oxygen concentration is too low, phosphorus removal may be reduced due to incomplete aerobic phosphorus uptake, nitrification will be adversely affected, and poor settling sludge could develop.

2.9.5 Sludge loading/age

Increase of the sludge loading and corresponding decreased of the sludge age could lead to a higher wasted sludge production. This resulted in an increased in the discharge of organically bound phosphate through the excess sludge and less phosphate needed to be removed through the storage of polyphosphate. Higher sludge loading also resulted in decreased nitrification, which in turn minimizes the inhibition of the Bio-P process by nitrate. This in turn increased the storaged capacity of the polyphosphate. The phosphate uptake by PAOs was determined by the conversion

rate of PHB in the aerobic and anoxic zones and the magnitude of the PHB fraction in the PAOs.

Grady and Daigger (1993) stated that the operating SRT for a BNR system had impacts on both organism selection and organic matter metabolism. They suggested that a sufficiently long aerobic SRT should be maintained to allow the poly-P bacteria to grow in the system and achieved phosphorus removal. They also stated that nitrification was one of the factors determining the selected aerobic SRT. If nitrification is required for the process, a sufficiently long aerobic SRT should be provided. Under longer aerobic SRT, more oxidation of organic matter can be obtained, leading to a higher rate of nitrogen removal under longer aerobic SRT. However, longer aerobic SRT may adversely affect biological phosphorus removal due to the secondary release of phosphorus because of an increase in endogenous respiration in the aerobic zone. Shao et al. (1992) obtained data from a full scale wastewater treatment plant in California and concluded that effluent phosphorus concentration decreased from 3.1 mg/L to 0.4 mg/L as the system SRT increased from 1.5 to 3.1 days. They also reported that higher phosphorus release per pound of total suspended solids and higher MLSS phosphorus content were observed when the system was operated at 3-day SRT. According to Mamais and Jenkins (1992), an SRT of 2.9 days or higher was required to obtain good phosphorus removal efficiency. Barnard (1983), recommended design of the system based on the minimum SRT for nitrification if nitrogen and phosphorus removal are obtained in the same system. If phosphorus removal could not be maintained, chemicals should be added to achieve phosphorus removal. Daigger et al. (1987) conducted a pilot-plant study using the VIP process and reported that nitrogen and phosphorus removal could be achieved when the system was operated at a process SRT of 5 days at the temperature of 20°C or above, while a process SRT of 20 days was required at a temperature of 12°C.

2.9.6 Anaerobic conditions/contact time

Anaerobic conditions were necessary for the uptake of acetate by PAOs. The required contact time depends on the amount of readily biodegradable substrate COD available and the maximum storage capacity of the PAOs.

2.10 Related Research

This thesis was to investigate effect of temperature and carbon on biological phosphorus removal, so this part indicated research was only temperature and carbon.

2.10.1 Temperature

Several factors may contribute to the seemingly contradictory resulted of temperature effect on EBPR performance and reaction rates. The resulted potentially could be explained through the use of different substrates, different system configurations, the used of different analytical techniques, the application of different operational conditions (SRT, different anaerobic and aerobic contact time etc.) (Brdjanovic et al., 1998) plus acclimated versus non-acclimated systems. Some studied had focus on the short-term (non-acclimated) effected of temperature on EBPR kinetics and performance while others had focused on long term (acclimated) effects. Therefore, it was difficult to directly compare the resulted of the studied. The resulted of the temperature effect on EBPR performance in the literatures can be divided into two broad groups:

a) Lower EBPR efficiency as temperature decreased.
b) No change or better EBPR performance as temperature decreased.

a) Lower EBPR efficiency as temperature decreased:

Shapiro et al. (1967) found that the anaerobic P-release rate decreased significantly when temperature was reduced by 10^{o}C. They reported that the temperature coefficient (Q10) to be 2.1-2.6 in the temperature range of 10-30^{o}C. Hashimoto and Furukawa (1984) investigated anaerobic P release in activated sludge over the temperature range of 12 to 28°C. They reported that P-release increased by a factor of 2.4 as temperature increased from 20-28^{o}C, and they determined an activation energy (Ea) value of 68.7 kJ/mol for P- release within the temperature range of 12-28^{o}C.

Jones et al. (1987) found 75 percent higher P-release and 30 percent higher uptake at 29^{o}C than those observed at 24^{o}C.

Spatzierer et al. (1985) investigated biological phosphorus removal in combination with simultaneous precipitation in three different full-scale BNR treatment plants located in Austria. They reported that biological P-removal was reduced under winter conditions with temperatures below 12oC. The impact of temperature on EBPR efficiency was investigated in a modified Bardenpho type process in Canada (Vassos et al., 1987). P-removal efficiency was reduced when the temperature was below 15^{o}C and further decrease to below this temperature significantly reduced plant phosphorus removal performance.

McClintock and Randall (1991) simultaneously operated side-by-side a lab scale Virginia Initiative Plant (VIP) configuration system and a conventional activated sludge (CAS) system using a feed of domestic wastewater supplemented with acetic acid to compare temperature effects on acclimated performance. EBPR was maintained for all temperatures investigated (20, 15, and 10^{o}C) while a 15-day SRT was maintained However, the EBPR functions were completely lost when the SRT of the VIP system decreased to 5 days even though COD removal remained at the same efficiency.

Mamais and Jenkins (1992) investigated the effects of SRT and temperature combinations on EBPR using continuous flow bench scale activated sludge system treating wastewater supplemented with 50 mg/l acetate over ranges of SRT and temperature of 2-4 days and 13.5-20^{o}C, respectively. The kinetic rates of the EBPR processes also were investigated during batch test experiments performed at 10 to 37^{o}C. With the inclusion of the McClintock data at 10^{o}C, it was stated that EBPR functioned efficiently and independently of SRT as long as SRTs were selected above 2.9 days for the temperature range studied. At lower SRT values EBPR capabilities might be lost at an SRT value that depends on temperature. The optimum temperature for aerobic P-removal was reported to be between 28-33oC and Q10 was calculated as 1.5-1.7 through the batch test experiment performed at 10-30^{o}C.

Marklund (1993) investigated low temperature effects on the performance of a full scale BNR plant located beyond the Arctic Circle in Sweden. The results of acclimated temperature studies using the SBR mode of operation showed that EBPR was maintained over the temperature range of 3-8^{o}C. However, the system did not meet the effluent limits of 0.5 mg P/l and 15 mg BOD/l except at 8^{o}C.

Jones and Stephenson (1996) suggested that the optimum temperature was 30^{o}C for anaerobic release and aerobic uptake of phosphate. EBPR was also observed at two extreme temperatures, 5 and 40^{o}C, but the efficiency of EBPR was reduced significantly. Activation energies were determined within 33-35kJ/mol and 39.5-41 kJ/mol for anaerobic P-release and aerobic P-uptake.

Brdjanovic et al. (1997) using a lab scale SBR, determined the short-term effects of temperature on EBPR performance and kinetics at 5, 10, 20 and 30^{o}C. Sludge that had been acclimated to 20^{o}C was used for the entire kinetic studies. The optimum temperature for anaerobic P release and acetate uptake was found to be 20^{o}C. However a continuous increase in aerobic P-uptake was obtained for temperature values up to 30^{o}C. The overall anaerobic and aerobic temperature coefficients were reported to be 1.078 and 1.057, respectively. The stoichiometry of EBPR was found to be insensitive to temperature changes.

Choi et al. (1998) used a lab scale modified UCT process fed with weak sewage with an average soluble COD of 100 mg/l, and investigated the BNR efficiency of the system over the temperature range of 20 to 5^{o}C. It was reported that the denitrification rate at 5^{o}C was roughly 10 times lower than at 10^{o}C. A rapid decrease was observed in P removal efficiency as temperature decreased from 20 to 5^{o}C. However recovery of P-removal at 5^{o}C was observed during continued operation.

Beatons et al. (1999) investigated the temperature effects on EBPR kinetics and performance in a SBR type process operated at temperatures of 20, 15, 10 and 5^{o}C with a constant SRT of 10 days. It was concluded that the aerobic P-release was

maximum over the temperature range of 15 –20^{o}C and all other reaction rates increased as temperature increased. Acetate breakthrough to the aerobic phase was reported at 5^{o}C because of incomplete P removal.

Krishna and Van Loosdrecht (1999) investigated the effect of temperature on storage polymers in a lab scale SBR unit fed with acetate. The specific acetate uptake rate was found to increase from 0.22 (C-mol/C-mol h) at 15^{o}C to 0.43 at 35^{o}C. However, the specific PHB formation rate decreased and the highest PHB formation and consumption was reported at 15^{o}C, the lowest temperature used in the investigation.

b) Unchanged or better P removal efficiency at cold temperatures:

Oldham and Dew (1979) investigated cold temperature effects on the system performance of a bench scale Bardenpho process. Over the temperature range of 18 to 6^{o}C, their results showed that EBPR efficiency was not affected by cold temperature and 90% P removal was achieved at 6^{o}C.

Sell et al. (1981) investigated low temperature (5, 10, and 15^{o}C) effects using an A/O process. They found that EBPR performance was not lost even when the temperature decreased down to 5^{o}C. Moreover, EBPR efficiency was 40% greater at 5^{o}C than at 15^{o}C. It was postulated that the EBPR bacteria are psychrophilic and work efficiently below 10^{o}C. They reported that temperatures above 10^{o}C resulted in a population shift from psychrophilic phosphate accumulating organisms to mesophilic non-phosphate accumulating organisms.

Krichten et al. (1983) obtained similar results to those reported by Sell et al. (1981), that is, increased P-removal was observed in an A/O process at 5^{o}C compared to 10oC and 15^{o}C.

Kang et al. (1985) operated a full scale A/O process in Pontiac, Michigan. The wastewater temperature did not affect on phosphorus removal efficiency at temperature was about 10 ^{o}C. The lowest effluent soluble and total phosphorus

concentrations of 0.3 and 0.4 mg/l, respectively, were observed at 11^{o}C, compared to 0.7 and 0.8 mg/l TP observed at 16 and 17^{o}C, respectively.

Van Groenestijin and Deinema (1985) showed that the P content of a pure culture of Acinetobacter was maximum at 5^{o}C (10%) and minimum at 35^{o}C (1.4%).

Daigger et al. (1988) achieved very good P-removal in a VIP process at 13^{o}C. However, temperatures as low as 5^{o}C did not change the system performance and an effluent P concentration of 1 mg/l was still reached, but more contact time was provided at the lower temperature.

Marklund and Morling (1994) used an SBR system and showed that EBPR was not lost even at temperatures as low as 3 – 8oC. However, a significant increase in effluent P concentration was reported when the temperatures were below 5 ^{o}C. On the other hand, biofloculation was enhanced at the lower temperatures.

Converti et al. (1995) used a modified A/O process to determine temperature effects on EBPR kinetics and performance at 5, 15, 25, 30 and 35 ^{o}C. The results showed that P removal efficiency varied between 60 to 62.5% over the studied temperature range. It was stated that the time necessary to achieve the desired level of P removal was strongly increased as the temperature decreased.

Jonsson et al. (1996) operated a full scale UCT plant in Helsinborg, Sweden between June, 1993 and July, 1994. The concentration of soluble phosphorus in the plant effluent was lower than 0.3 mg/l even at temperatures below 10 ^{o}C as long as enough VFA potential was presented.

Helmer and Kunst (1997) used a lab scale Johannesburg process treating domestic wastewater with supplemental peptone to show that a drop in temperature to 10^{o}C and then 5^{o}C had no significant effect on the efficiency of EBPR in spite of reduced P release observed at 5^{o}C. The dominant organisms at 5^{o}C were identified as facultative anaerobic microorganisms, which showed the best ability to store poly-P

under cold temperatures. The temperature coefficients were reported as 1.20 and 1.28 for anaerobic P-release and aerobic P-uptake, respectively.

Brdjanovic et al. (1998) extended their previous studies to include long term temperature effects on EBPR performance, kinetic rates and molecular effects. It was found that EBPR efficiency was low at 10^{o}C with an 8-day SRT, but complete removal was achieved when the SRT was increased to 16 days. The P removal efficiency was still excellent at 5^{o}C when the SRT value was increased to 32 days. While only a very slight deviation from the short term temperature coefficient under anaerobic condition was observed (1.078 vs. 1.085), the temperature coefficients for oxygen uptake and PHA consumption were significantly changed following temperature acclimation. Electron microscopy and dry denaturing gradient get electrophoresis (DDGGE) techniques showed the existence of a population shift when the temperature dropped to 5 ^{o}C.

Panswad et al. (1999) investigated the long-term effect of temperature on EBPR using an A/O process and feeding synthetic wastewater. The experiments were performed at 5, 15, 25, 35, and 40 ^{o}C, and showed that P-removal efficiency was not adversely affected by temperatures below 25 ^{o}C. Instead, P removal efficiency was reduced by 28% and 39% at 35^{o}C and 40 ^{o}C, respectively. Complete P removal was achieved for three temperatures studied (5, 15 and 25 ^{o}C). Interestingly, nearly no P-release was reported at 40^{o}C although 61% P- removal was observed. Panswad et. al., (2003) studied the effect of temperature on the microbial community of EBPR sludge and found that PAOs were dominant at 20 ^{o}C but that glycogen accumulating organisms (GAO) and ordinary heterotrophs became dominant at higher temperatures. At 30 ^{o}C the GAOs were the dominant group while ordinary heterotrophs dominated at 35 ^{o}C. The results indicated that PAOs were lower range mesophiles or psycrophiles.

Several studied have been conducted on the effect of temperature on EBPR. Brdjanovic et. al. (1997) studied the short-term (hours) effect of temperature in the range 5 – 30 ^{o}C and found a maximum anaerobic phosphate release at 20 ^{o}C. The aerobic conversion rates increased in the interval 5 – 30 ^{o}C. The overall anaerobic and

aerobic temperature coefficients (θ) were 1.078 and 1.057, respectively. The stoichiometry under anaerobic conditions was insensitive to the temperature changes, but some effect on the aerobic stoichiometry was observed. The findings on temperature dependency and temperature coefficient were similar to previous studies (Mamais and Jenkins, 1992). Brdjanovic et. al. (1998) also studied the long-term (weeks) effect of temperature in the range 5 – 30 ^{o}C, and found that the anaerobic stoichiometry was relatively insensitive to temperature changes, but that that the temperature had a marked influence on the anaerobic kinetics. The temperature coefficient in the long-term experiments was similar to the value found in the short-term experiments (θ = 1.085 versus 1.078, respectively). The long term effect of temperature on aerobic P-uptake was moderate although a marked temperature influence was found for some of the metabolic processes under aerobic conditions such as PHA consumption and oxygen utilization rate (OUR). The results from analysis of the microbial community using molecular ecological techniques showed that the microbial population changed with changing temperature and consisted of several (five to seven) different types of bacteria. Optimum temperatures for phosphate uptake have been reported to be as high as 28 – 33 ^{o}C, (Mamais and Jenkins, 1992). However, good results have also been reported at lower temperatures.

Erdal et. al., (2003) investigated the effect of a temperature change from 20 ^{o}C to 5 ^{o}C in a laboratory scale activated sludge process operated in a University of Cape Town (UCT) configuration (anaerobic – anoxic – aerobic series of reactors). The study concluded that the temperature effects on EBPR reaction rates were consistent with other biological and chemical reactions (i.e. decreased with decreasing temperature) and that wash out of PAO can occur at low temperatures if the sludge retention time (SRT) is too short. However, provided that the SRT was sufficient to avoid wash out, the PAO population increased at low temperatures resulting in an improved phosphorus removal. The authors concluded that the PAO are psycrophilic bacteria and temperatures of 10 ^{o}C or lower give them an advantage relative to non-PAOs in activated sludge systems. The results are in accordance with previous findings for EBPR at low temperatures with respect to SRT (Daigger et. al., (1987) and good P-removal Barnard et. al., 1985).

In an earlier study at Kelowna, Canada, based on four years of monitoring data, Vassos et. al., (1987), found that an overall phosphorus removal of 68 % could be achieved at temperatures at or below 15 ^{o}C, while the treatment efficiency increased to 85 % with temperatures above 15 ^{o}C, indicating a temperature boundary at 15 ^{o}C. The studies referred to above are all from activated sludge based systems. In a laboratory scale experiment with synthetic wastewater in a fixed film bio reactor Gonzales-Martines and Wilderer (1991) found that the phosphate release increased with decreasing temperature in the temperature range of 15 – 25 ^{o}C. However, the phosphate concentration in the effluent at the end of the anaerobic – aerobic cycle was the same at the different temperatures. The over all removal of phosphate was thus not affected by the temperature.

2.10.2 Carbon source

The performance of BNR system is strongly affected by the characteristic of wastewater. The BNR performance for treating domestic or municipal wastewater is sensitive with wastewater characteristics. In fact, this wastewater is contained low organic matter (low BOD or COD), especially in the suitable form for PAOs, DPB, and denitrifiers such as RBCOD and VFAs. In order to increase biodegradable substrates for improvement BNR performance, it needs to supplement external carbon source to the ways:

a) External input of acetate, propionate, glucose, methanol, and ethanol.
b) External fermentation of municipal solid wastes.
c) Acid formation of municipal solid wastes.
d) Acid fermentation of primary sludge.

Concentration of COD in the relation to nutrients has great effect on simultaneous nutrient removal. Since organic substrate competition between phosphorus accumulating organism (PAOs) and denitrifying bacteria might frequently occur, plant configuration that exert selective pressure in favor of PAOs denitrifying bacteria are strongly recommended, such kinds of plants are particularly suitable for low COD wastewater, where lack of carbon affects the nutrient removal efficiency.

Short Chains Fatty Acids (SCFAs) and non-SCFAs as carbon sources

On an average basis the COD to phosphorus ratio should be at least 35, or the BOD to phosphorus ratio should be at least 20 to achieve good phosphorus removal (SCOPE, 1998). Randall et al. (1992) more explicitly stated that a ratio of BOD5 to total phosphorus of 20:1 or greater was needed to reliably achieve an effluent with a total phosphorus concentration of 1.0 mg P/l or less, when gravity sedimentation was used as the last treatment step. For total COD to total phosphorus ratio, (Randall et al,l992) stated that ratios of 45 or greater are necessary. According to Janssen (1999), 1 g of phosphorus could be removed when 10 g of readily biodegradable carbon source was available. According to Reddy (1998), 50 mg COD/mg P removed was a conservative number for North American municipal wastewater, and was recommended for design purposes. In their work, Ekama and Marais.(1984) suggested 50 to 59 mg COD/mg P was necessary to remove phosphorus efficiently from South African wastewaters. For higher ratios, the authors stated that it was very likely removals down to 0.5 mg P/l can be achieved. However, most important for good phosphorus removal to occur was the kind of carbon source anaerobic available. In general carbon sources are subdivided in so-called short chain fatty acids (SCFAs) and non-SCFAs.

In initial study concerning EBPR authors continuously refer to good EBPR activity in connection with carbon sources belonging to the group of short chain, low molecular monocarboxylic acids (C1-C6) also called short chain fatty acids (SCFAs) or volatile fatty acids (VFAs). Fuhs and Chen, (1975), Potgieter and Evans,(1983), Malnou (1984), Ekama et al.(1984b), Arvin and Kristensen (1985) and Comeau et al.(1987b) all report a more important phosphorus release when acetate or propionate are used instead of other substrates. According to (Reddy,1998) an accepted rule of thumb is that the readily available organic matter concentration, which corresponds to the group of SCFAs, within the initial anaerobic zone, must be more than 25 mg COD/l to accomplish significant EBPR. Increase of VFA will increase the phosphorus release and the organic storage in the anaerobic zone, up to some optimum VFA-to-phosphorus ratio.

Conversely, studies by Randall (1995) and Chapin,(1997) show that high concentrations of acetic acid (greater than 400 mg COD/l) can cause failure of EBPR processes. The group of non-SCFAs studied in relation to EBPR performance mainly comprises the oxocarboxylic acid, pyruvate, hydroxy fatty acids such as lactic acid and malic acid, di-acids such as oxalic acid, malonic acid, succinic acid and maleic acid, monosaccharides such as glucose and disaccharides such as lactose and sucrose. Starch, a glycogen-like polymer, is also relatively often tested for its EBPR activity. These components are considered because of either their appearance in wastewater or their production during fermentation or glucose metabolism (e.g. pyruvate). Depending on the carbon sources, different anaerobic release rates/amounts and PHA uptake rates and compositions can be encountered.

Type of carbon source affects significantly in the simultaneous removal of nitrogen and phosphorus. Easily biodegradable carbon substrate such as acetate, time required for complete denitrification and P release was shorter than methanol at the same concentration. Glucose was the effective substrate hence they did not recommend it for biological nitrogen and phosphorus removal.

Erdal et.al monitored COD utilization, phosphorus release and uptake, PHA and glycogen storage and utilization of the system. The steady state data showed that PHA storage, glycogen production and system performance were influenced by the COD:TP ratio. The system phosphorus removal performance decreased as COD:TP ratio decreased and some deterioration in overall performance occurred at the lowest COD:TP ratio.

CHAPTER III
MATERIAL AND METHODS

This study was an experimental reach to investigate the effect of temperature on biological phosphorus removal. The experiment consists of two main parts of the experimental units;

a) A field study for BPR observation in Chongnonsi WWTP which VFA uptake, phosphorus release and uptake, percentage of phosphorus in biomass and the efficiency of phosphorus removal were studied.

b) The experiment with lab-scale SBRs in the laboratory to imitate BPR configuration in Chongnonsi WWTP were conducted. The resuls of this part were expected for better explanation of BPR occurrence in Chongnonsi WWTP.

The schematic flow of experiments in this study was illustrated in Figure 3.1.1.

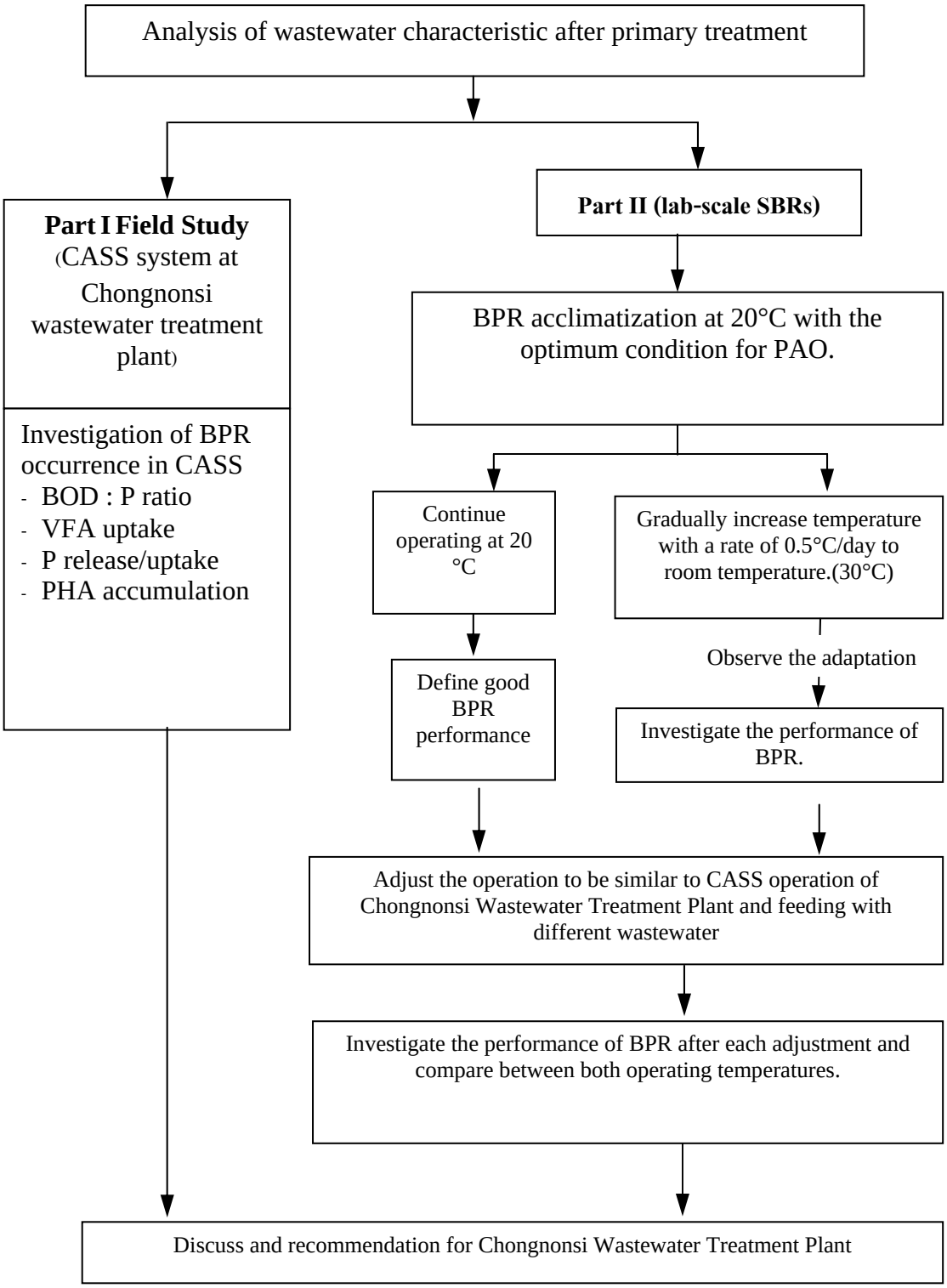


Figure 3.1.1 The schematic flow of experiments.

Part I:

3.1 A Field Study in Chongnonsi Wastewater Treatment Plant

This part was to investigate the biological phosphorus removal performance in Chongnonsi WWTP. Chongnonsi WWTP has been constructed in a four-storage building floors, which each floor has been installed with six CASS basins, totally twenty four CASS basins. During the investigation of this study there were only eleven basins operated. The capacity of this plant was designed at 200,000 to 300,000 m^3/d, but current quantity of wastewater treated by this plant was only 120,000 to 130,000 m^3/d. Therefore, this Chongnonsi WWTP is currently operated only half of design capacity.

In this study, only two CASS basins were randomly selected those of which located on first floor named as CASS basins C and D. As each CASS basin composed of three consecutive zones, three sampling points (Figure 3.1.2) for each basin were considered. The influent wastewater was sampling from influent wastewater sump and effluent wastewater was sampled from cascade outfall of the plant, as illustrated in Figures 3.1.3 and 3.1.4.

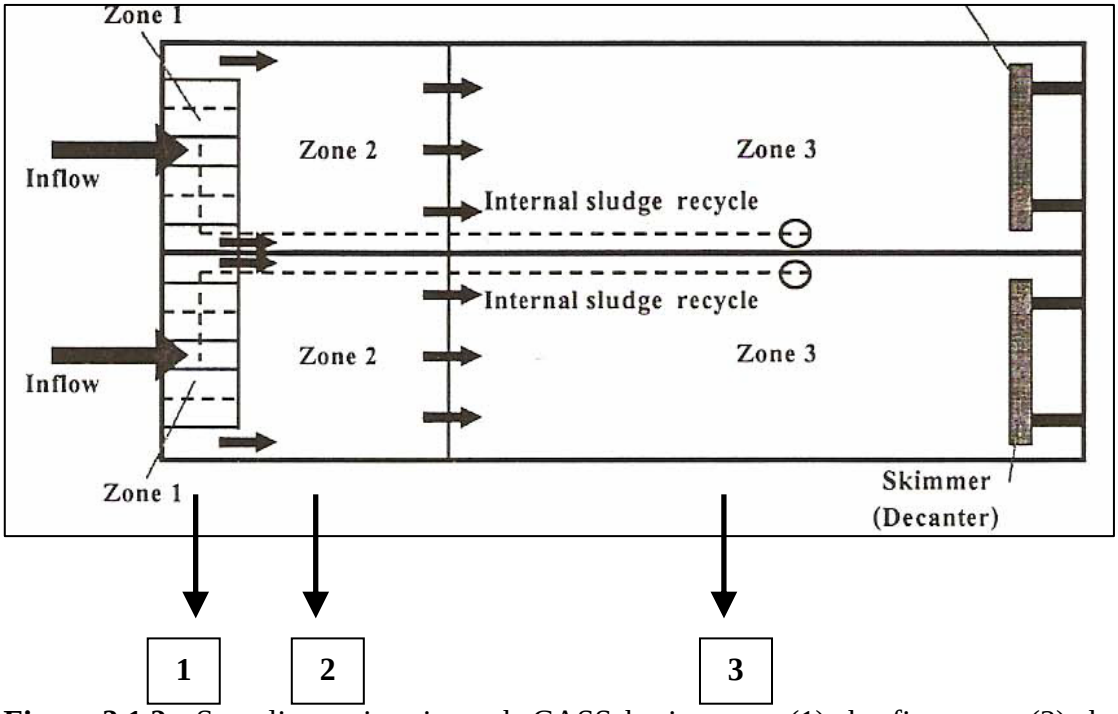


Figure 3.1.2 Sampling points in each CASS basin; zone (1) the first zone (2) the second zone, and (3) the third zone.

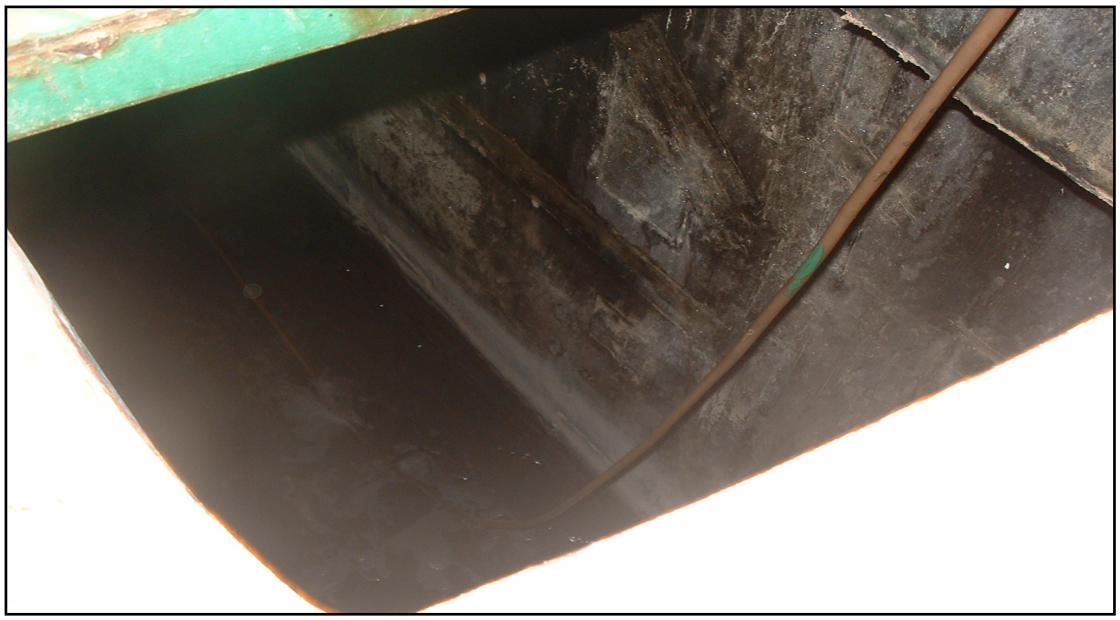


Figure 3.1.3 Sampling point of influent wastewater of CASS system.

Figure 3.1.4 Sampling points of effluent wastewater from Chongnonsi WWTP.

3.2 Process in This Study of the First Part

3.2.1 Monitoring COD, TKN, and phosphorus removal efficiencies in Chongnonsi WWTP. Phosphorus release and uptake in CASS basins and phosphorus content were studied for comparison BPR performance between low or higher temperature, and consideration of carbon feed effect.

3.2.2 Sampling would be taken from the following locations;

3.2.2.1 Influent into CASS reactors of Chongnonsi WWTP.

3.2.2.2 Mixed liquor in each zone of CASS basins.

3.2.2.3 Effluent wastewater of Chongnonsi WWTP.

3.2.2.4 Sludge in CASS basins.

3.2.3 Analyzed parameters and sampling frequency were shown in Table 3.2.1.

Table 3.2.1 Sampling locations and frequency of analyze parameters for Part I : A field study in Chongnonsi WWTP

Parameter	Influent*	CASS basins**			Effluent
		1st zone	2nd zone	3rd zone	
pH	•	•	•	•	•
DO	•	•	•	•	•
Temperature	•	•	•	•	•
Total BOD	•				•
Soluble BOD					•
Total COD	•				•
Soluble COD	•	•	•	•	•
VFA	•	•	•	•	•
SS	•				•
MLSS		•	•	•	
SV30				•	
Total TKN	•				•
Soluble TKN	•	•	•	•	•
Soluble NO_3-N	•	•	•	•	•
TP	•				•
Soluble P	•	•	•	•	•
Sludge PHA		•	•	•	
%P in sludge		•	•	•	

Remarks : *Influent in this study was an effluent from primary treatment of Chongnonsi WWTP into CASS reactors

**Collected as mixed liquor in CASS reactors

- Sampling and analysis for three times a week

3.3 Part II: An Experiment with Lab-Scale SBR in the Laboratory.

- This experimental part was conducted to help define the genuine cause of poor BPR performance in Chongnonsi WWTP. Two presumptive causes were introduced, i.e. effects of high temperature and low carbon feed. Five consequtive phases of operation were set up to investigate those two causes.
- Two SBRs reactors were both started up with temperature controlled at 20°C and using the operation condition and synthetic wastewater that suitable for enhancement of biological phosphorus removal process.
- After good biological phosphorus removal occurred in both reactors, one of them will continue operating at temperature of 20°C. The second reactor will be adjusted to room temperature with increasing rate of 0.5°C/day. The adaptation and performance of biological phosphorus removal in this reactor will be observed and compared with 20 °C SBR.
- Then, the operating configuration of both SBR reactors will be adjusted to imitate CASS operation in Chongnonsi Wastewater treatment Plant as similar as possible. Consequently, efficiency of biological phosphorus removal will be monitored.
- Then, wastewater synthesized to be similar to domestic wastewater, were fed to investigate the effect of low carbon feed. Again, BPR performance was observed and also compared between different operating temperatures.
- The last phase was fed with real domestic wastewater from Chongnonsi WWTP to control the effect from using different wastewaters.
- Two SBR system was consist of five phases to determine the effect of temperature and carbon source which followed procedure;
- The operating condition may be adjusted to enhance better biological phosphorus removal if it is possible.
- Conclusions and suggestions are proposed with consideration of the studied results.
- Sampling would be taken from the following locations; Influent of lab-scale SBRs, Mixed liquor in reactors, Effluent of lab-scale SBRs and Sludge in lab-scale SBRs

Analyzed parameters and sampling frequency were shown in Table 3.3.1.

Table 3.3.1 Sampling locations and frequency of analyzed parameters for Part II : An experiment with lab-scale SBR in the laboratory.

Parameter	Influent	Reactor 1**	Reactor 2**	Effluent
pH	D	D	D	D
DO		D	D	
Temperature		D	D	
Total BOD	3/W			3/W
Soluble BOD	3/W			3/W
Total COD	3/W			3/W
Soluble COD	3/W	3/W	3/W	3/W
VFA	3/W	3/W	3/W	3/W
SS	3/W			3/W
MLSS		5/W	5/W	
SV30				
Total TKN	2/W			2/W
Soluble TKN		2/W	2/W	
Soluble NO_3-N		2/W	2/W	
TP	3/W			3/W
Soluble P	3/W	3/W	3/W	3/W
sludge				
PHA		2/W	2/W	
%P in sludge		2/W	2/W	

Remarks :**Mixed liquor in reactors would be filtrated before analysis

D analyzed every day

2/W analyzed 2 times/week

3/W analyzed 3 times/week

5/W analyzed 5 times/week

3.4 Reactor Set-Up

A laboratory-scale of SBR reactors was set up and conducted in Laboratory Section of Sanitary Engineering Department, Faculty of Public Health, Mahidol University.

Two lab-scale SBRs system used in this studied and made from stainless steel with square shape, as illustrated in Figures 3.4.1 and 3.4.2.

The internal size of reactor was 25x25x69 cm. with the level of water about 26.9 cm, resulting in working volume about 16.8 liters as illustrated in Figure 3.5. In addition, influent tank and effluent tanks made from plastic with volumes of 20 L (SBR condition) and volume of 100 L during CASS process. The influent tank that used to fed wastewater to system was mixing between water and nutrient before fed to two SBRs system by submersible pumps.

3.4.1 Accessories

Motors used in this study work with speed of 200 round/hours. A twelve-inch plastic propeller was attached with a motor to provided mixing during the cycle step of anoxic/anaerobic.

Air pump was used to supply oxygen during the cycle step of aerobic.

In addition, two submersible pumps were used for feeding wastewater and withdrawing treated effluent from the reactors. The schematic flow of lab-scale SBRs was shown in Figure 3.4.3.

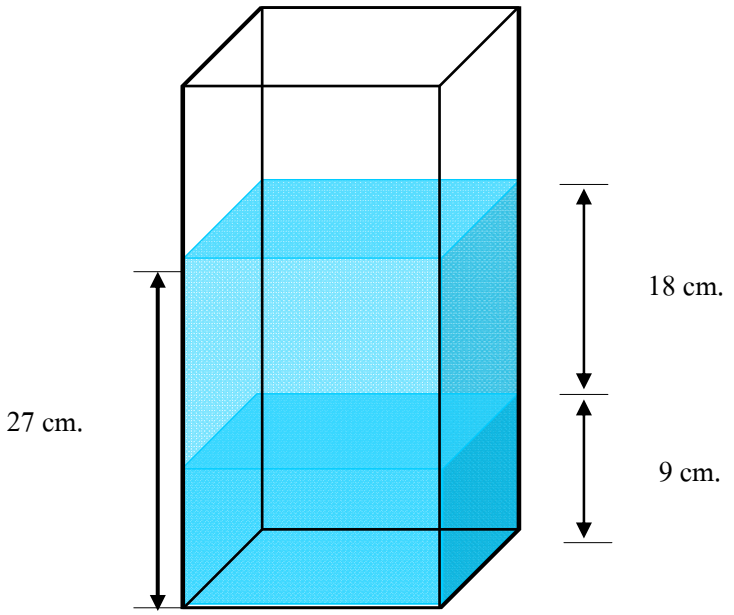


Figure 3.4.1 The SBR System for operated in the first and the second phases.

(a)

(b) (c)

Figure 3.4.2 Two SBR used in this study:

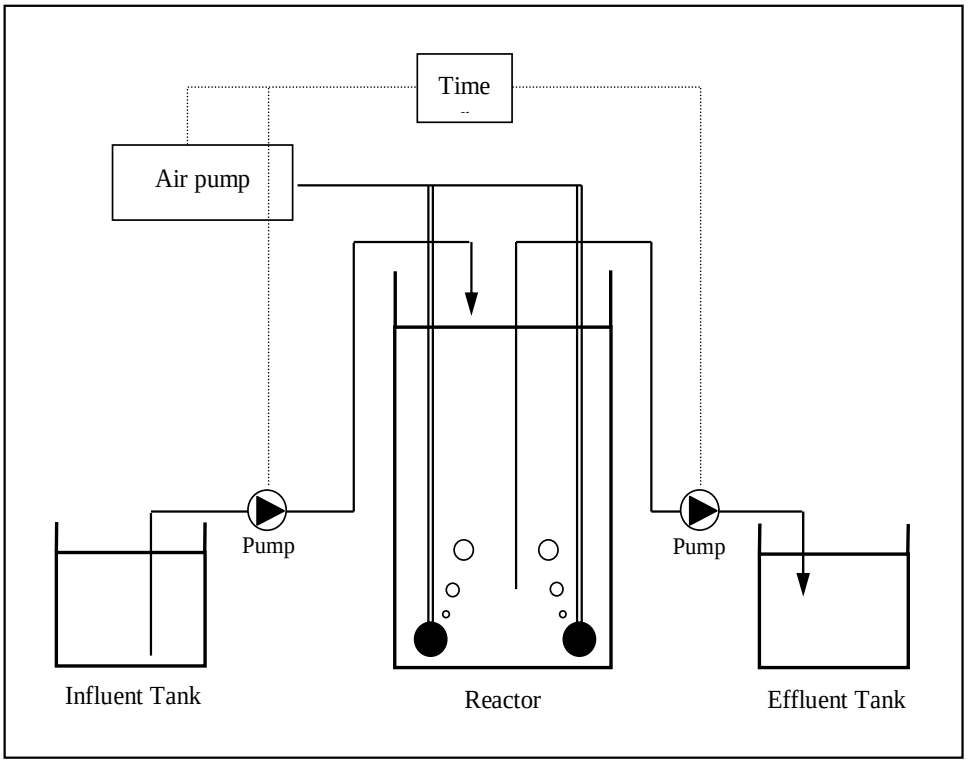


Figure 3.4.3 A lab-scale SBR setup

3.5 Seed Sludge, Synthetic Wastewater, Synthetic Domestic Wastewater and Domestic Wastewater

Seed Sludge

The seed sludge system was taken from a return activated sludge pipeline of CASS system. Real domestic wastewater used in this past was collected from sumps of CASS influent. This influent was partly treated by the preliminary and primary treatments of Chongnonsi WWTP.

3.6 Acclimatization in SBR Systems

The seed sludge was fed to SBR system and controlled initial of MLSS concentration of 4,000 mg/L. This was gradually fed step by step starting from 25%, 50%, 75% and 100% of total flow rate (33.3 ml/min or 2 l/h). This acclimatization period took about till reaching steady state 73 days. The excess sludge was done at the end of aerobic condition (APPENDIX C). DO concentration in anaerobic and aerobic conditions was controlled lower than 1 mg/l and about 3 mg/l, respectively. Temperature was kept at about 20 °C for both reactors during acclimatization period.

3.7 Experimental Procedures and Operation Conditions

The experiments in the second part were divided into five phases as followed:

3.7.1 The first phase

The first is ‘Acclimatization phase’, which aimed to stimulate good biological phosphorus removal, therefore, synthetic wastewater containing 300 mg COD/l (from acetic acid 220 mg COD/l and nutrient broth 80 mg COD/l) and 20 mg/l phosphorus was fed into those two reactors. Both reactors were operated at constant temperature of 20^{o}C until they reach a steady state.

3.7.2 The second phase

The second the first phases to investigate the effect of temperature increase on BPR efficiency by gradually adjust operating temperature in the reactor R2 from 20 to around 30^{o}C with the rate of not more than 0.5^{o}C/day. The same synthetic wastewater as used in the previous phase was still fed into both reactors. Therefore, the reactor R1 was continued the same operation to the first phase. In this phase, when the steady state was reached, the temperature effect on BPR was determined by making a comparison between the reactors R1 (20^{o}C) and R2 (30^{o}C).

3.7.3 The third phase

Both R1 and R2 was changed the operation from SBR system to like-CASS system following by the operation of CASS in Chongnonsi Wastewater Treatment Plant.

Therefore, the operation changed to the third phase the accident design was found in this phase. For like-CASS operation, total fill + aeration took about 75 min, which composed of 30 min anaerobic condition and 45 min aerobic condition. This operation and that of CASS of Chongnonsi WWTP were not exactly identical due to configuration of reactors. For CASS in Chongnonsi WWTP, influent at the minute of 30 and after still pass through anaerobic condition, while those in SBR reactors were exposed to only aerobic condition.

3.7.4 The fourth phase

In the fourth phase, same operating conditions were continued after the third phase. The synthetic domestic wastewater with COD and phosphorus concentrations similar to real domestic wastewater was synthesized and fed to both reactors. The effect of small loadings in synthetic domestic wastewater was evaluated when the steady state was reached.

3.7.5The fifth phase

In this phase, both reactors were fed with real domestic wastewater collected from Chongnonsi Wastewater Treatment Plant between June to July 2007. This phase was to investigate the effect of low organic carbon when real domestic wastewater was used

The stepwise operation was concluded in Figure 3.7.1

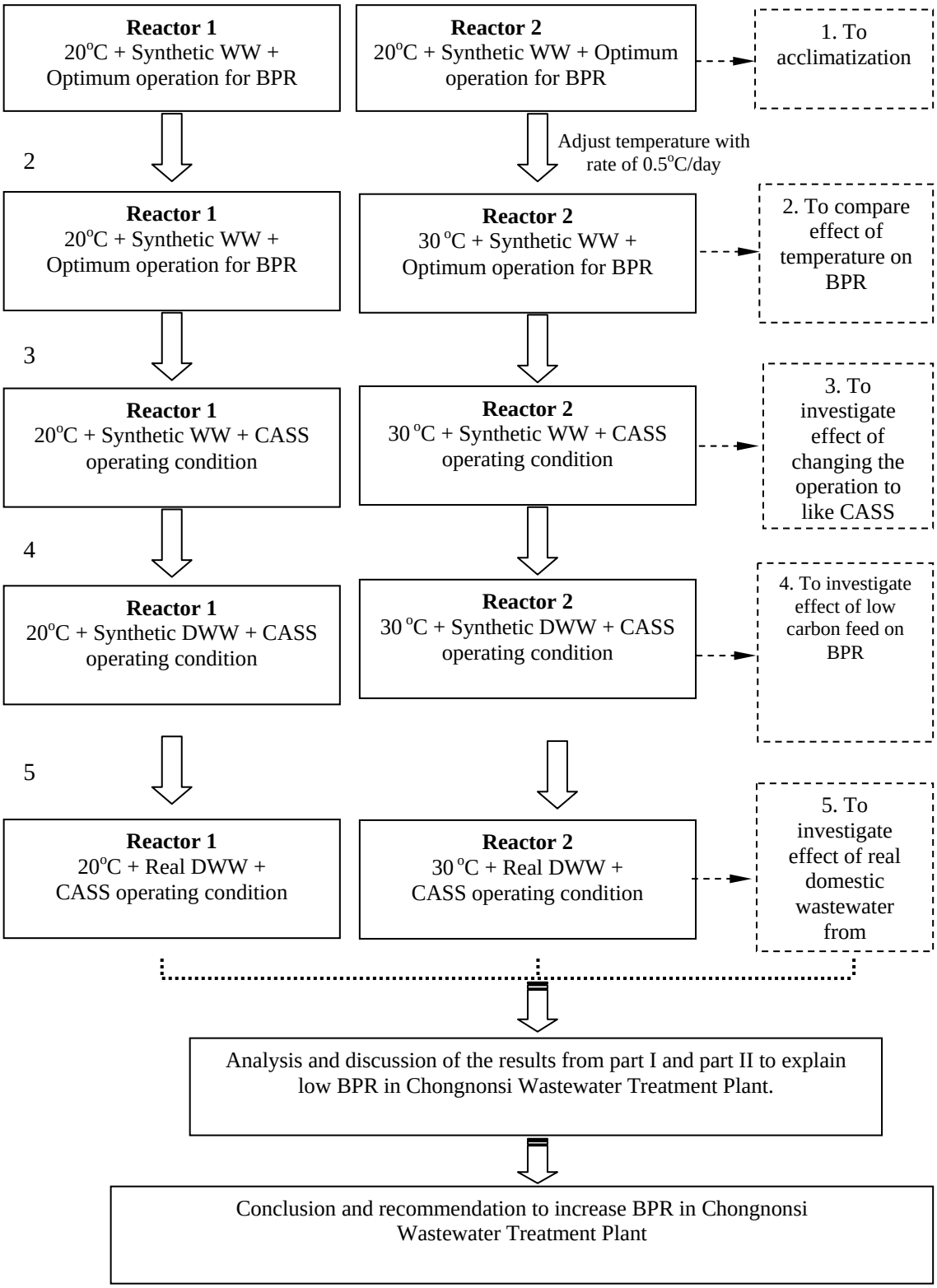


Figure 3.7.1 Conceptual frameworks in the experiment of part II

Operatiing cycle time

The first phase and the second phase was operated in conventional SBR configuration, feeding reaction, draining periods as illustrated in Figure 3.7.2 (a).

The third phase though the fifth phase was operated following the operation at CASS in Chongnonsi WWTP. Therefore, volume of feeding was 4.8 L and volume of retained water was 12.06 L as illustrated in Figure 3.7.2 (b).

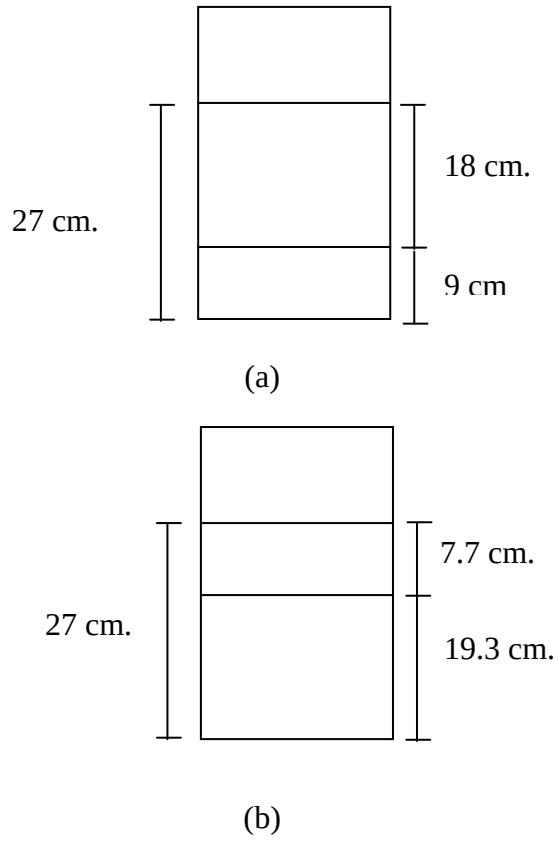


Figure 3.7.2 (a) Cycle pattern during the first and the second phases
(b) Operating during the third through the fifth phases.

The experimental procedure of this part was summarized in Figure 3.7.1 and the detail of operation conditions were presented in Table 3.7.1**.** The composition of synthetic wastewater and synthetic domestic wastewater were reported in Table 3.7.2. The cycle time of operation as illustrated in Table 3.7.3.

Table 3.7.1 The operating conditions of SBR system used in this study

Parameters	Operation Phases				
	The first	The second	The third	The forth	The fifth
	The reactor 1 (R1)				
Control Conditions					
HRT,h	18	18	4.5	4.5	4.5
SRT, d^{-1}	10	10	10	10	10
Independent Conditions					
Temperature (°C)	20	20	20	20	20
Influent wastewater	SWW	SWW	SWW	SDWW	DWW
	The reactor 2 (R2)				
Control Conditions					
HRT	18	18	4.5	4.5	4.5
*SRT, d^{-1}	10	10	10	10	10
Independent Conditions					
Temperature (°C)	20	30	30	30	30
Influent wastewater	SWW	SWW	SWW	SDWW	DWW

Remark: SWW = Synthetic Wastewater

SDWW = Synthetic Domestic Wastewater

DWW = Domestic wastewater

* = The SRT calculation as illustrated in Appendix C.

Table 3.7.2 The Composition of synthesis wastewater all five phases. (Appendix A and B)

Substances	Dose (per liter)	
	The reactor 1 (R1)	The reactor 2 (R2)
Nutrient broth	80 mg (COD = 80 mg)	30 mg (COD = 30 mg)
CH_3COOH	0.20 ml (COD = 220 mg)	0.07 ml (COD = 70 mg)
KH_2PO_4	70 mg (16 mg as P)	8.98 mg (2 mg as P)
$NaHCO_3$	420 mg	138.39 mg
$MgSO_4.7H_2O$	2.88 mg	0.49 mg
$FeCl_3.6H_2O$	1.5 mg	0.5 mg
$CaCl_2$	9.6 mg	2.4 mg

Table 3.7.3 Operation cycle times all five phases.

Phases	The cycle time
the first to the third phases	Fill 10 minutes Anaerobic 4.5 hours Aerobic 6 hours Excess Sludge at end of aerobic condition Settle 1 hour Draw 10 minutes
Times in each cycle 12 hours	
the forth to the fifth phases	Fill + aerate 75 minutes Anaerobic 30 minutes Aerobic 45 minutes Excess Sludge at end of aerobic condition Settle 50 minutes Draw 45 minutes
Times in each cycle 3 hours	

3.8 Sampling and Analytical Methods

3.8.1 Sampling Methods

3.8.1.1) Chongnonsi WWTP

In wastewater and samples in Chongnonsi WWTP were almost collected at the same hour of days, three days a week Tuesday, Thursday and Saturday in the morning (between 9.20 to 10.00 am). The collected domestic wastewater was stored in refrigerator at 4 °C unitl feeding to the experimental system.

3.8.1.2) SBR System

For the SBR system, the performance were observed and controlled by routine determination of influent, mixed liquor in each condition and effluent. The system was considered to reach a steady state condition when the MLSS concentration, COD, TN, TKN and TP removal efficiencies remained fairly constant over a period of several days. The mixed liquor was taken from aerobic condition of SBR by grab sampling. The influent was collected from feed tank and the effluent was collected from the effluent tank by grab sampling method and kept in refrigerator about 4°C until analytical determination. Samples represented a steady state were determined continuously about 10-12 days.

3.8.2 Analytical Methods

The concentrations of COD, TKN and TP in the influent, anaerobic and aerobic conditions, and effluent were measured in non filtrated samples, while SCOD, TKN, NO_3 and TP concentrations in each zone were filtrated by GF/C. The sludge settleability was determined by using the SV_{30} test, phosphorus content (% P TSS) was analyzed from collected sludge at the end of aerobic condition. PHA, PHB and PHV contents were determined by using the methanolysis-GC method developed by Hart (1994), with modifications described by Punrattanasin (2001) (Appendix D). Most of the parameters were analyzed according to Standard Methods (APHA et al., 2005) as listed in Table 3.8.1.

3.9 Statistical Analysis

3.9.1 Descriptive analysis: The concentrations and/or percentage of removal efficiencies of COD, TKN, NO_3 and TP of SBR system would be described by mean, minimum and maximum values.

Table 3.8.1 The methods for sample analysis

Parameters	**Analysis Methods**
pH	pH meter
DO	Direct measurement with a YSI Model 54 A SSI DO meter
SV30	Imhoff cone
SS	Filtration through GF/C Whatman filters and measuring The mass lose after passing dried at 105ºc
MLSS	Filtration through GF/C Whatman filters and measuring The mass lose after passing dried at 105ºc
MLVSS	Filtration through GF/C Whatman filters and measuring The mass lose after passing heated at 550ºc
Total COD	Closed reflux titrimetrix method.
SCOD	Closed reflux titrimetrix method .Filtration through GF/C Whatmam filters.
TKN	Nitrogen determination with digestion,distillation units and titration
STKN	Nitrogen determination with digestion,distillation units and titration,after filtration through GF/C Whatman filters
NO_3	Brucine methoda after filtration through GF/C Whatmam filters.
TP	Nitric-Sulfuric digestion method and follow by vanadomolybdate method
SP	Nitric-Sulfuric digestion method and follow by vanadomolybdate method, after filtration samples through 0.45 um membrane filter.
PHA	Methanolysis-GC (Punrattanasin, 2001).

CHAPTER IV
RESULTS AND DISCUSSION

This study was to investigate effects of temperature and low carbon feed on biological phosphorus removal (BPR) in Chongnonsi Wastewater Treatment Plant (Chongnonsi WWTP) as a case study. The experiments divided into two parts; Part I was to investigate performance of BPR in cyclic activated sludge system (CASS) of Chongnonsi Wastewater Treatment Plant, especially according to seasonal temperature varying in Bangkok, Thailand. Part II was to investigate effects of temperature and carbon feed on BPR by using two sequencing batch reactors (SBR) implemented with temperature control devices. This part required seeding acclimatization, which intentionally was conducted under some conditions appropriate for BPR occurrence, especially at temperature of 20^{o}C. Once both reactors exhibited BPR activities under steady state, one of two reactors was adjusted to room temperature of about 30^{o}C with a rate of not faster than 0.5°C per day while another reactor was kept the operating temperature of 20^{o}C. Then, the SBR operation of both reactors was changed to be the like of CASS system in Chongnonsi Wastewater Treatment Plant. In the final phase, real domestic wastewater was used to compare with synthetic wastewater.

Some abbreviations are used in this Chapter occasionally, i.e. an acronym “R” is an abbreviation of word “Reactor” and the numbers behind represent the identification of the reactors used in this experiment. For example, R1 refers to the first SBR. In addition, acronyms “C” and “D” stand for words “CASS reactor C” and “CASS reactor D” of Chongnonsi Wastewater Treatment Plant, respectively. The numbers behind ‘C’ and ‘D’ represent the zone within each CASS reactor, such as C1 refers to the first zone of CASS reactor C.

4.1 Part I, Chongnonsi Wastewater Treatment Plant

Chongnonsi wastewater treatment plant (Chongnonsi WWTP) is one of the Bangkok Metropolitan Administration (BMA) wastewater treatment plants designed for biological nutrient removal. Their service area of about 22 km^2 covers Sathon, Yannawa, Bangrak and Bangkholam districts**.** Due to the limitation of land in metropolitan area, this plant was constructed in the building-like structure and a cyclic activated sludge system (CASS) has been implemented. The CASS is a fed-batch single sludge – single basin nutrients removal methodology, which does not require primary or final settling, tanks (Earth Tech, 2004). Chongnonsi WWTP building has four floors, each floor installed with six CASS basins, totally twenty four basins for treating the design capacity about 200,000 m^3/d. Currently, this plant has not been operated with its full capacity, there are only eleven active CASS basins working at a time because the volume of received wastewaters are only about 100,000-120,000 m^3/d. However, only two CASS basins on the first floor, named basins C and D, were selected for the observation.

The objective of this part was to investigate BPR performance in this Chongnonsi WWTP, compared between winter and summer seasons of Bangkok.

Performance of Chongnonsi Wastewater Treatment Plant

This experimental part started on November 21, 2006 and finished on July 23, 2007, which covered lower and high temperatures of Bangkok. During this investigation period, characteristics of influent wastewater and treated effluent were illustrated in Table 4.1.1. The influent wastewaters fed into Chongnonsi WWTP contained COD concentrations in a range of 60-150 mg/l, BOD of 52-80 mg/l, TKN of 3-13 mg/l and TP of 1.2-6 mg/l, of which the average of COD/TP ratio was around 36:1. The treated effluents characteristics shown in Table 4.1.1 were resulting in the COD, TP and TKN removal efficiencies of 73, 44 and 42%, respectively.

Table 4.1.1 Characteristics of the influent wastewater and treated effluent of Chongnonsi WWTP during November 21, 2006 to July 23, 2007.

Parameters	Influents	Effluents
COD	60-150	20-30
BOD	52-80	10-20
TP	1.2-6	1-2.1
TKN	3-13	1-5
DO	0-2	6-7
pH	7.2-7.3	7.1-7.2
Temp	28-30*	28-30

Remark; * Influent temperature location is close wastewater tank is ground base and cause of high temperature than temperature of mixed liquor.

DO concentrations

Figure 4.1.1 shows that DO concentrations in the influents and treated effluents were in the range of 0-2 mg/l and 5-7.5 mg/l, respectively. High DO concentrations in the effluents of the plant resulted from CASS supernatant withdrawal through Syphon Box Culvert type of draining ditch and cascade type of outfall to Chao Praya River as shown in Figure 4.1.2.

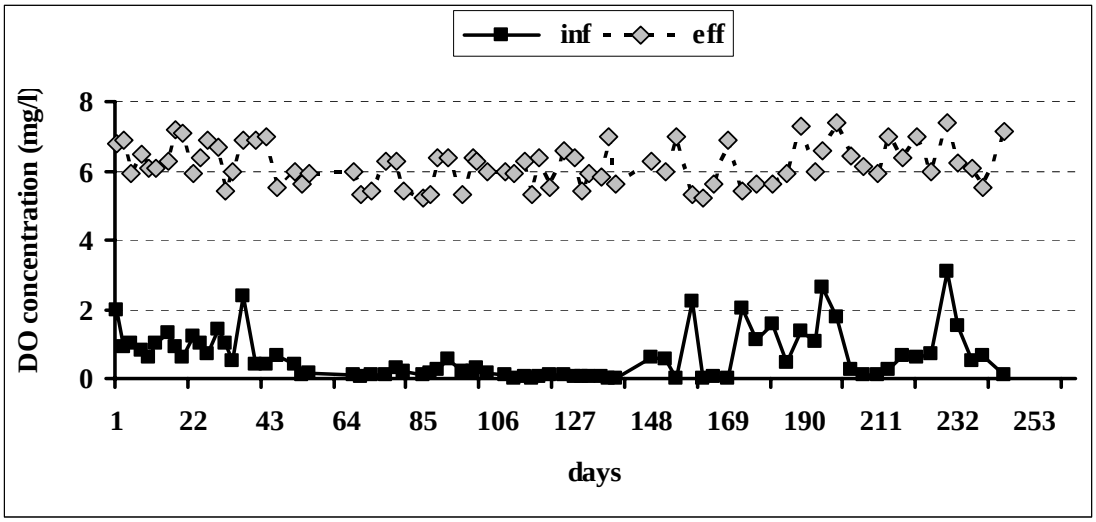


Figure 4.1.1 Profile of DO concentration in the influents and effluents of Chongnonsi WWTP.

Figure 4.1.2 The cascade outfall of treated effluent discharged to Chao Praya River.

Wastewater temperature

During the investigation period, the temperature of wastewater varied from 28 to 30°C because influent wastewater location is the under ground floor and the weather quite sultry condition and receiving heat thermal by engine from preliminary treatment, which results in the temperature increase in the range of 28 - 30°C. However, CASS basins situate in building, so the temperature of mixed liquor in CASS basins varied in the range of 25-30 °C of Bangkok seasonal temperatures and was divided into three periods. That is, the first twenty four days were around 29°C (December 2006), then they decreased to around 25^{o}C during the days 25 to 90 (January – February 2007), and they increased to about 30^{o}C since the day 110 through the end of investigation period (July 2007), as illustrated in Figure 4.1.3.

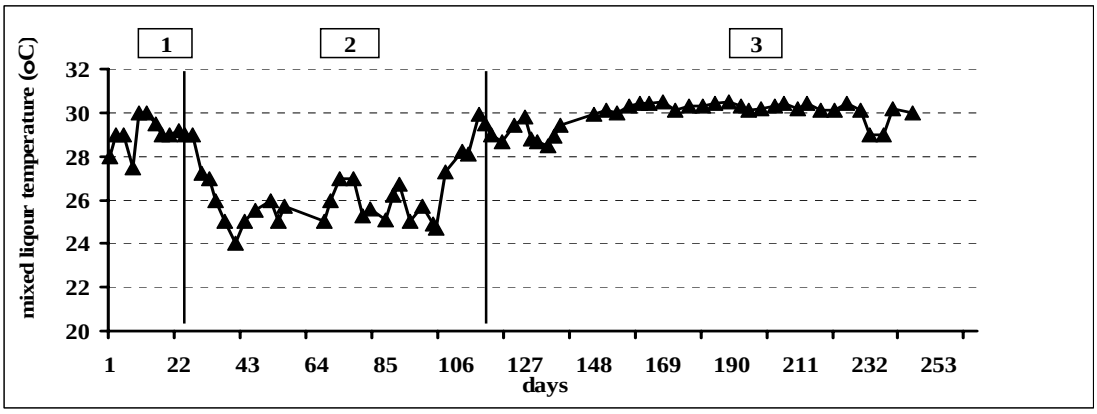
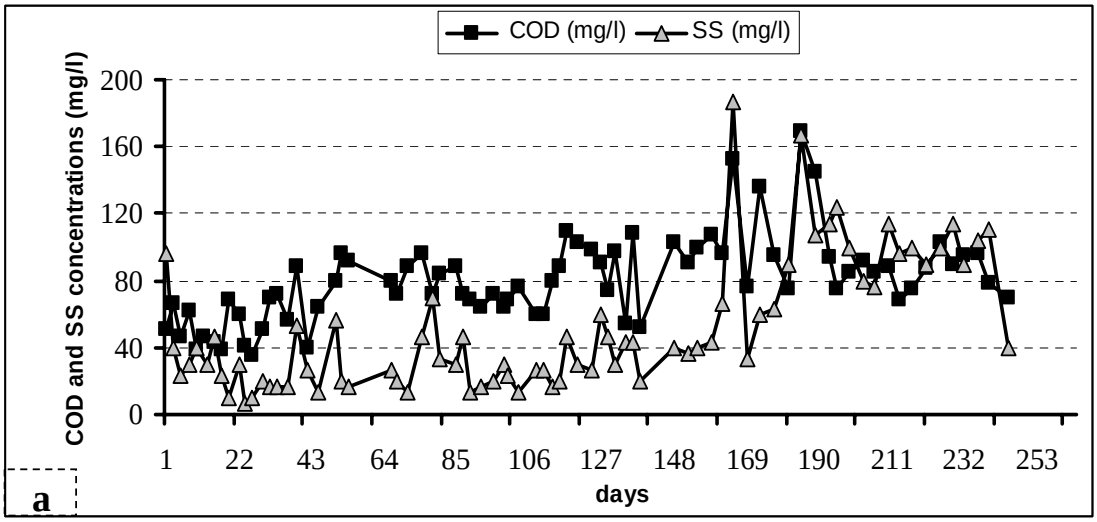


Figure 4.1.3 Temperature of mixed liquor in CASS basins of Chongnonsi Wastewater Treatment Plant

The fluctuation of influent characteristics

As mentioned above, the investigation was done during November 2006 to July 2007, which covered both dry and rainy seasons of Bangkok. The fluctuation of wastewater characteristics occurred as shown in Figure 4.1.4. Typically, the strength of wastewater should be diluted during rainy seasons because of rainfall contamination, but those shown in Figure 4.1.4 were not as expected. COD, TKN, phosphorus and SS concentrations of the influents during the third period (mostly rainy season) were higher than the first and the second periods, which rainfall did not appear.

This untypical appearance was a result of a BMA policy, Klong Suay Nam Sai. During dry season, BMA tried to keep the water quality of canals (or 'Klong' in Thai) in Bangkok area by diluting with water drawn from Chao Praya River. On the other hand, water in canals was occasionally drawn into Chao Praya River because BMA had to maintain their drainage capacity during rainy season.



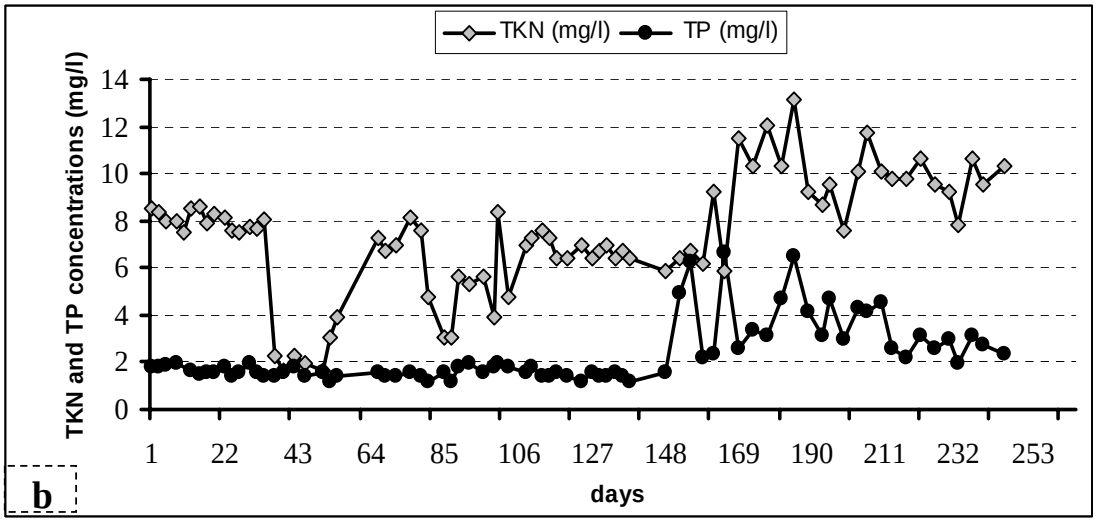
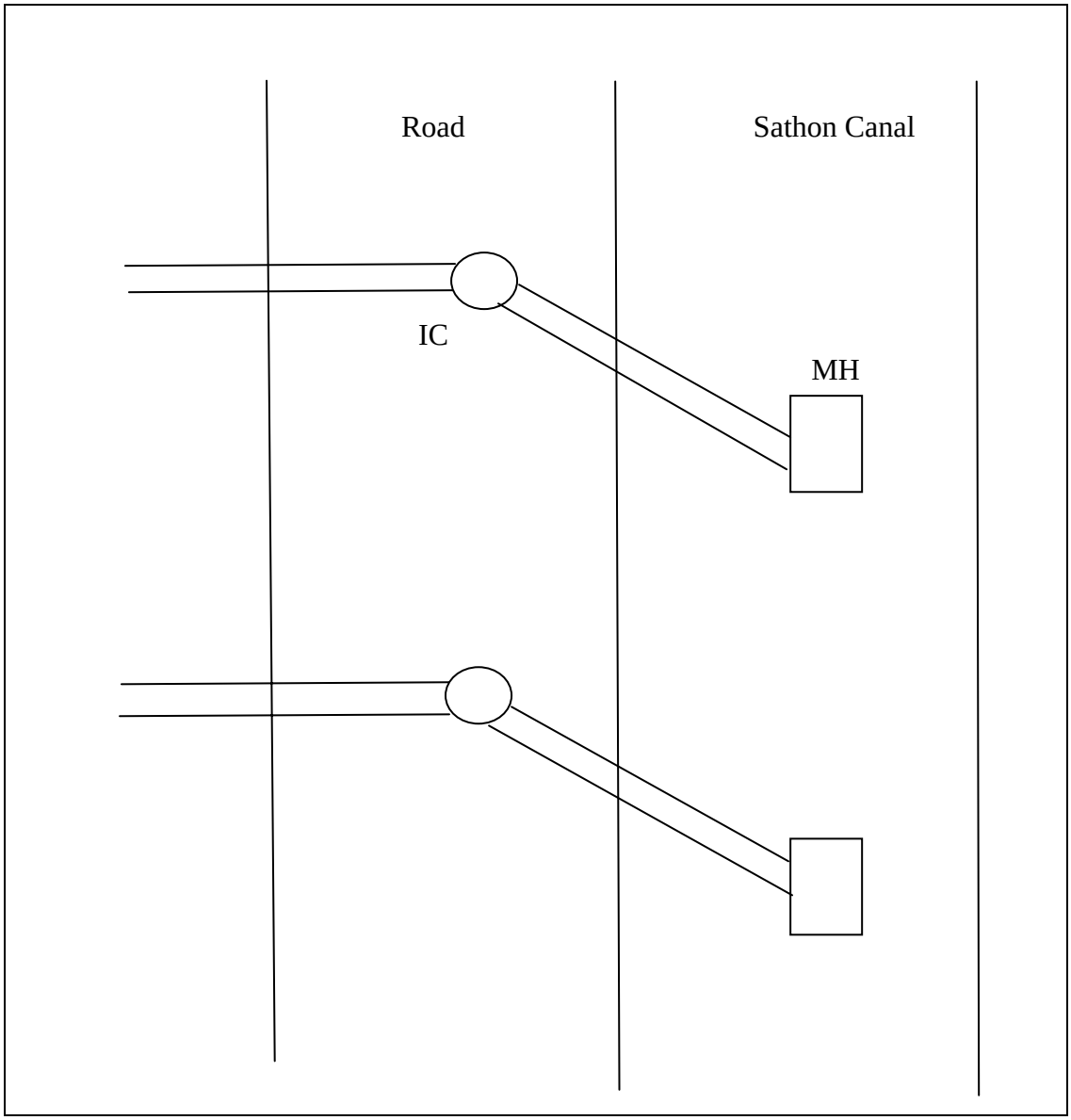


Figure 4.1.4 COD, TKN, phosphorus and SS concentrations in the influents of Chongnonsi WWTP; (a) COD and SS concentrations
(b) TKN, phosphorus TKN, phosphorus concentrations

The BMA collection system was a network of several canals and Chao Praya River as partly simplified in Figure 4.1.5. During dry season, water was pumped from Chao Praya River into canals for dilution and additional flow. This resulted in higher water level in the canal than the pipeline of the interceptors as shown in Figure 4.1.6 (a). Therefore, water from the canals could overflow through the collection system and contaminate the collected wastewater. This could be the reason of the weak concentrations of wastewater (low COD, TKN, TP and SS) fed into Chongnonsi WWTP during dry season. (The COD, TKN, TP and rainfall in 2006 as illustrated in Appendix H)

During the rainy season, water level in canals was lower to maintain their drainage capacity. Hence, the canal water could not overflow into the interceptors and not contaminate the collected wastewater as shown in Figure 4.1.6 (b). The Chongnonsi WWTP received only domestic wastewater without dilution effect, resulting in higher concentrations of some parameters even during rainy season. This practice (canals water were drawn into and off) mostly depended on the raining events and rainfall intensity. Figure 4.1.7 shows the graph of rainfall intensity in Sathon

canal, the nearest pumping station of the Chongnonsi WWTP, which there was some correlation to graphs of concentrations in Figure 4.1.4.



Note IC Inter Ceptor
MH Man Hole
1 Inlet station
2 Chongnonsi WWTP

Figure 4.1.5 Flow diagram of collection system.

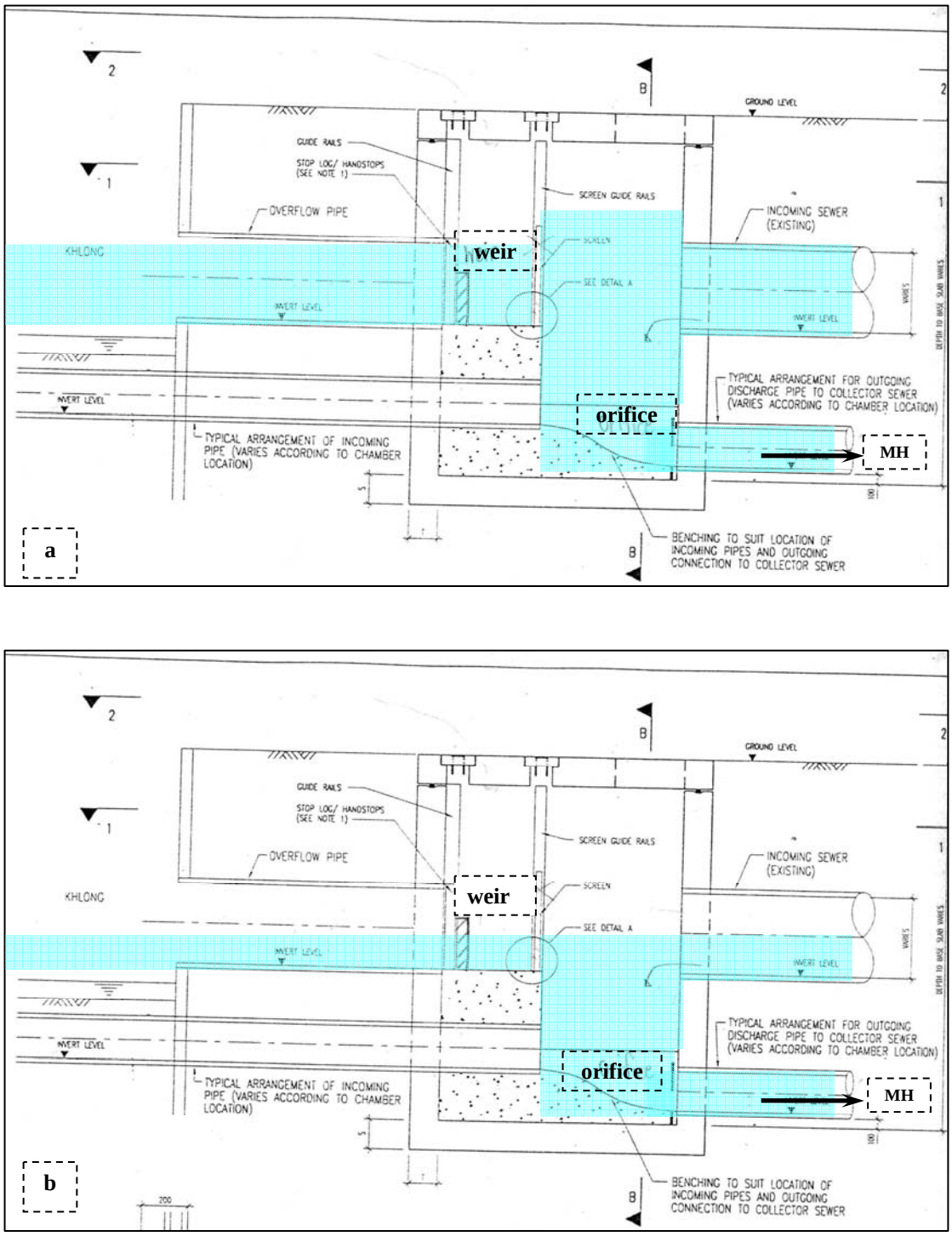


Figure 4.1.6 Water level variation in canals with practicing the BMA policy; (a) dry season and (b) rainy season (receive from BMA)

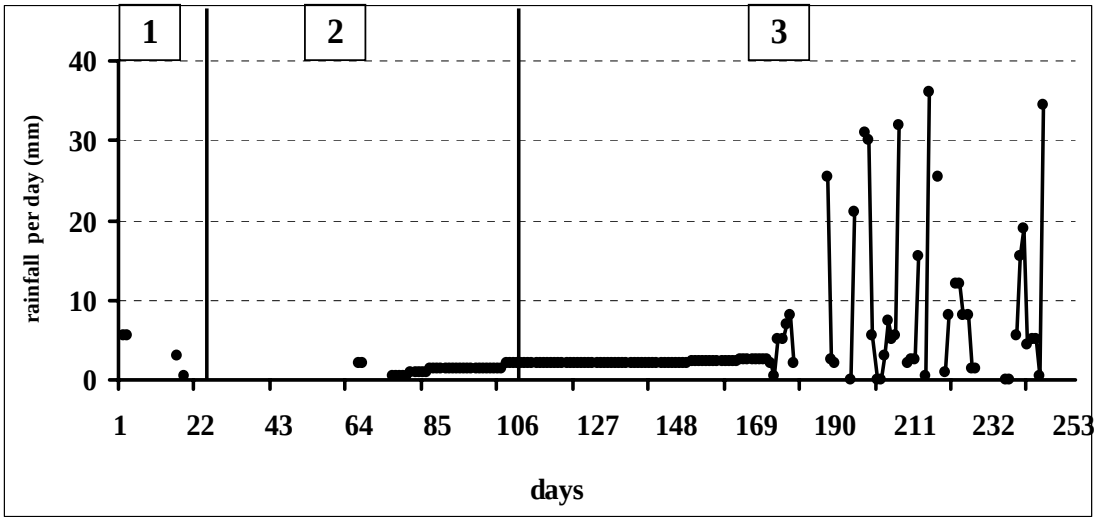


Figure 4.1.7 The rainfall intensity in Sathon canals recorded during the investigation period (BMA, www.bma.go.th 6 Feburary 2008)

During eight months of the investigation (November 21, 2006 - July 23, 2007), the efficiency of TCOD removal was in a range of 55-77%, while TKN removal was in a range of 69-80% and total phosphorus removal was in a range 36-57% as illustrated in Figure 4.1.8. The removal efficiencies of TCOD and TKN were not quite high during the first and the second periods, they slightly increased in the third period because of higher influent concentrations. The variation of wastewater strength obviously appeared on total phosphorus removal efficiency, which significantly increased in the third period.

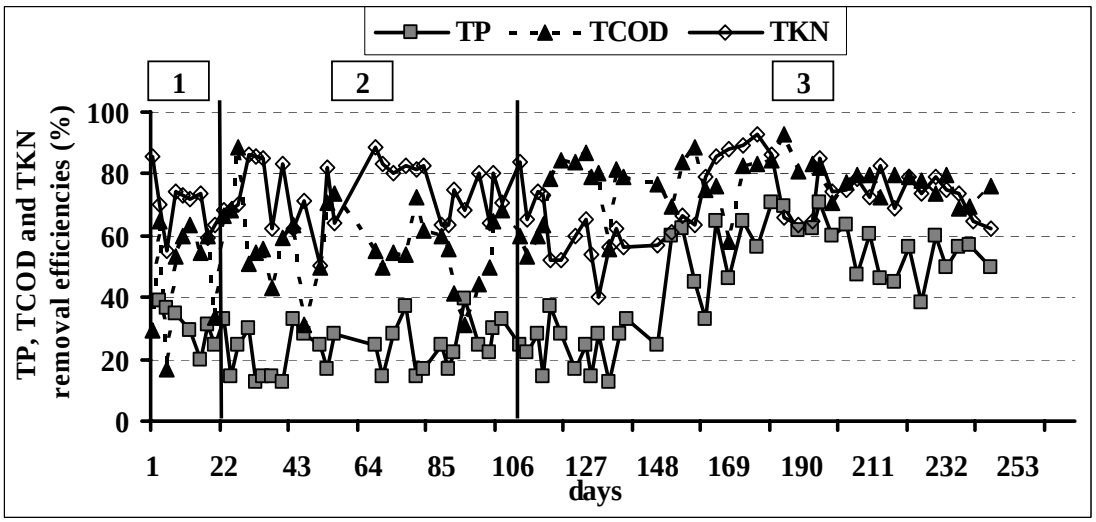


Figure 4.1.8 The removal efficiencies of COD, TKN and total phosphorus.

4.2 CASS basins C and D

The characteristics of CASS basins C and D in study periods during November, 2006 – July, 2007, such as temperature, the percentage of phosphorus (%P in biomass) pH values and DO, MLSS, COD, TKN, and TP concentrations were investigated in this study as illustrated in Table 4.2.1. The acronym C1 C2 C3 and D1 D2 D3 were an abbreviation of word CASS basins C and D in the first the second zone and 3, respectively.

The average wastewater temperatures of basins C and D were in the range of 25-30 °C. The average temperature in each zone of CASS basins C and D did not different which followed the Bangkok seasonal temperature during the investigation period.

The average pH values of both CASS basins C and D were in the range of 7.1-7.6. The range of pH values in BPR process was recommend about 7.5-8.0 (Liu et al, 1996; Janssen et al, 2002; Sperling and Chernicharo, 2005).

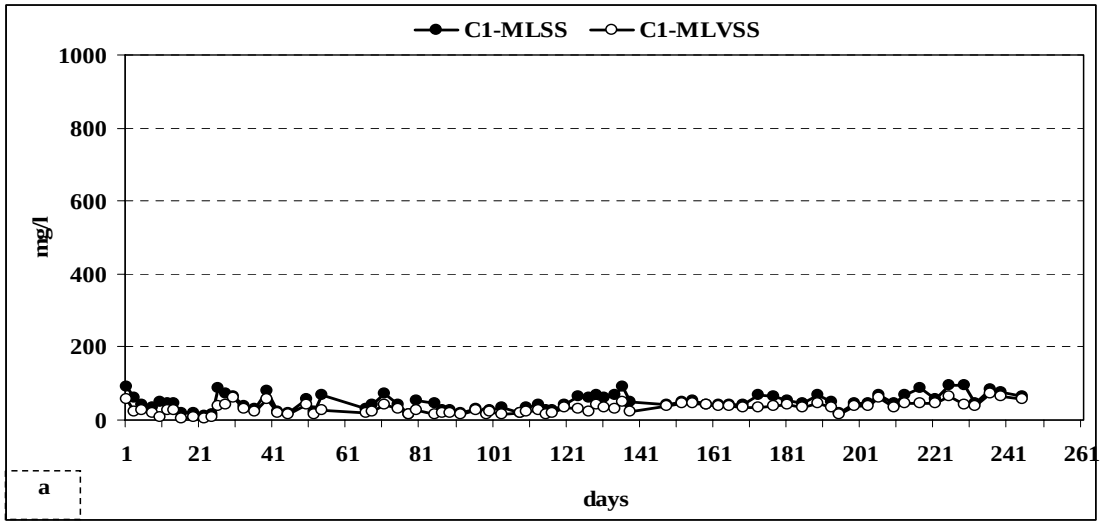
The average DO concentrations in the first zone and the third zone were similarly except in the second zone of both CASS basins C and D. As a result, the average DO concentrations in the first zone were higher than the second zone even though that the aerators disappeared in the first zone. The mechanism in the preliminary treatment and the turbulence that may causes of high DO concentrations in this zone. The average DO concentrations in the third zone for CASS basins C and D similarly, because of this zone is an aerobic zone with many aerators. Therefore, the average DO concentrations in this zone were in the range of 3.3 and 3.3 mg/l. Interestingly, the average DO concentrations in the second zone were less than the first zone even though did not have the aerators in the first zone and had different in CASS basins C and D. Observation, the aerators in CASS basins C worked very well with complete mixed between influent and sludge around basin and affected of the average DO concentrations about 1.0 mg/l.

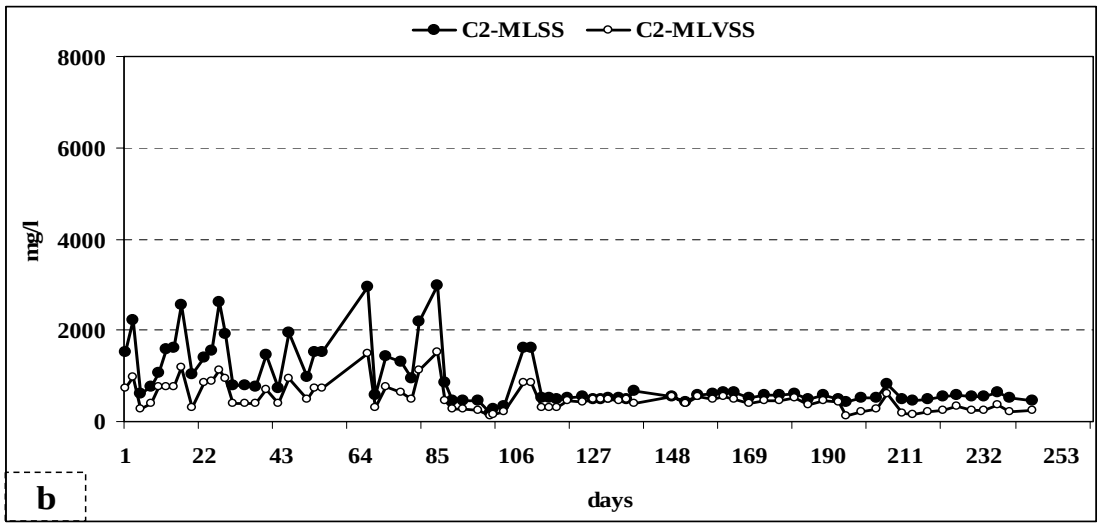
Table 4.2.1 The characteristic of CASS basin C and D during November 2006-July 2007.

Parameter	Unit		CASS basin C			CASS basin D		
			C 1	C 2	C 3	D 1	D 2	D3
Temperature	°C	min	24.0	24.0	24.0	24.0	24.0	24.0
		max	30.5	31.0	30.5	30.5	30.5	30.5
		mean	28.0	28.0	28.1	28.0	28.0	28.0
		SD	2.1	2.2	2.0	2.1	1.9	2.1
pH		min	7.1	7.1	7.1	7.0	7.0	7.2
		max	7.6	7.5	7.6	7.5	7.4	7.5
		mean	7.2	7.3	7.3	7.2	7.1	7.2
		SD	0.1	0.1	0.1	0.1	0.1	0.1
DO	mg/l	min	0.7	1.0	2.7	0.9	0.1	3.0
		max	2.6	2.3	3.8	2.2	0.3	4.0
		mean	1.7	1.5	3.2	1.2	0.1	3.4
		SD	0.5	0.4	0.2	2.2	0.0	0.2
MLSS	mg/l	min	10	180	2700	6.7	13	1240
		max	96	2987	6700	313	1920	7630
		mean	48	936	4464	49	660	2792
		SD	22	688	987	48	362	1487
COD	mg/l	min	21	12	5.5	23	11	2.9
		max	145	89	41	155	77	35
		mean	58	34	15	56	35	15
		SD	28	15	8	25	16	7
TKN	mg/l	min	0.5	0.3	0.3	0.8	0.3	0.2
		max	13.0	9.5	4.7	12.0	7.9	5.1
		mean	6.9	4.4	1.6	5.6	3.6	1.7
		SD	3.2	3.0	1.2	2.9	2.1	1.2
TP	mg/l	min	1.0	1.2	1.0	0.8	1.2	1.0
		max	6.1	6.5	3.1	5.9	6.5	3.9
		mean	2.6	3.2	1.6	2.5	3.3	1.6
		SD	1.4	1.3	0.5	1.4	1.4	0.6
%P (TSS)	%	min			0.2			1
		max			3.7			4.7
		mean			1.8			2.8
		SD			0.7			1

Remark; The total sample were 78 samples.

The DO concentrations was different was in CASS basin D because aerators may work not well and the mixing with big bubble found only the middle that spread around basin. The sampling station was the edge of basin, so the investigation periods had low DO concentration were in range 0.01-0.03 mg/l. Therefore, the low DO concentration in the second zone of CASS basin D may occur the good BPR process better than CASS basin C. The DO concentration in anaerobic condition recommended was in the range of 0.0-0.2 mg/l (Shehab et al., 1996).





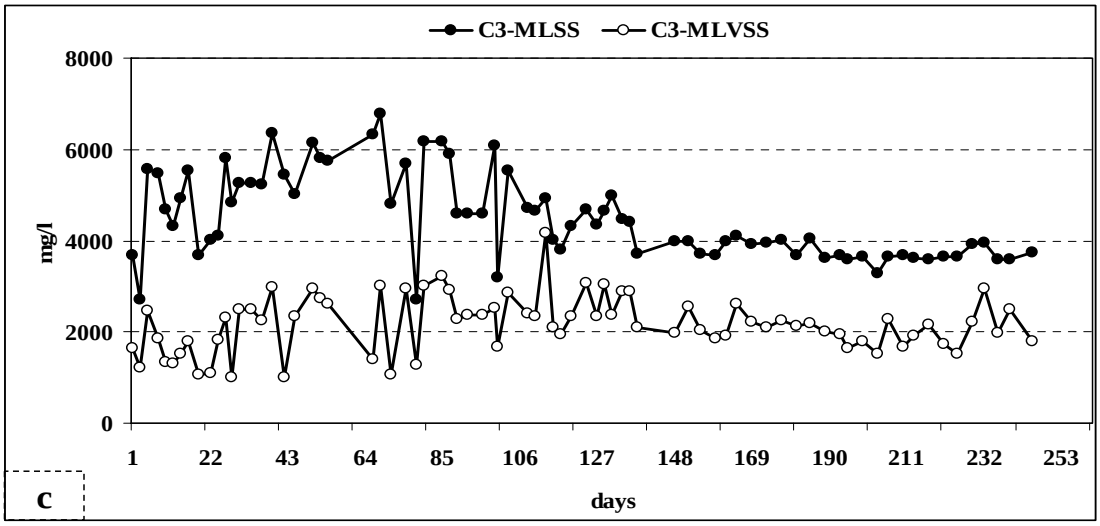
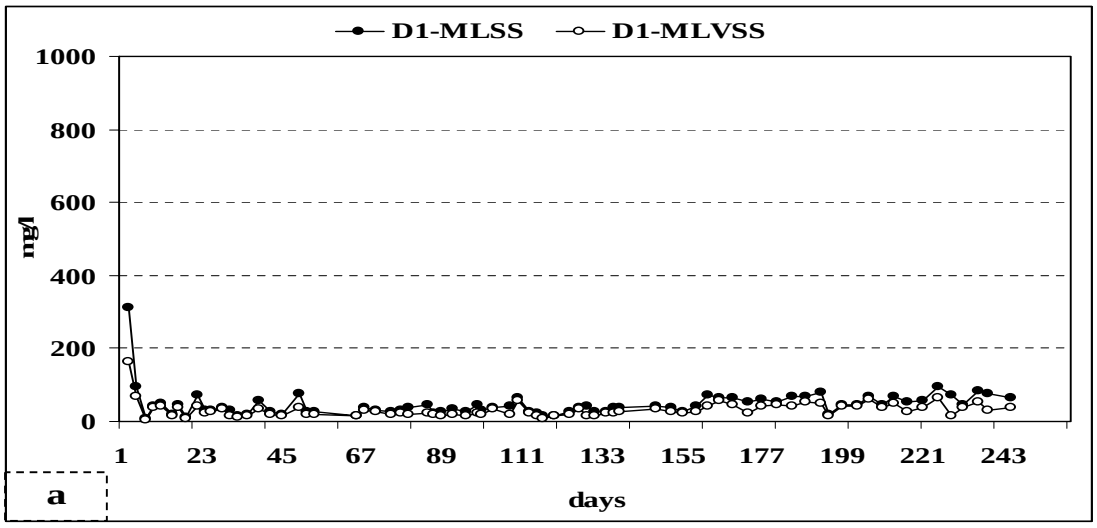


Figure 4.2.1 MLSS in CASS basin C of (a) the first zone (b) the second zone and (c) the third zone



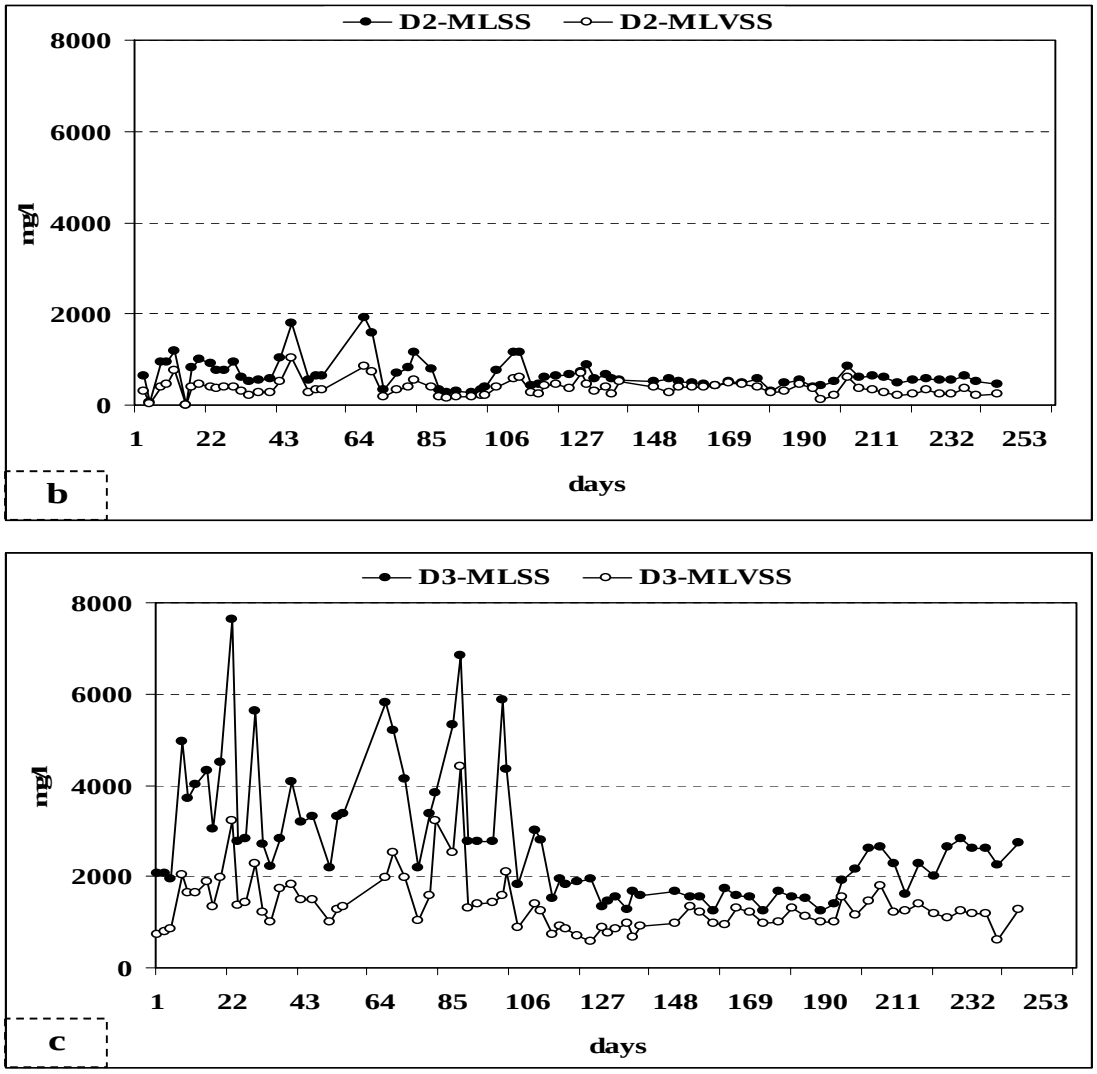


Figure 4.2.2 MLSS in CASS basin D of (a) the first zone (b) the second zone and (c) the third zone

Figure 4.2.1 and 4.2.2 show the MLSS concentrations of both CASS basin C and D, which MLSS concentrations in creased from the first zone to the third zone. Interestingly, the sludge was returned from the third zone to the first zone, but the lowest MLSS concentrations were found in the first zone. Therefore, the disappearance of aerators and did not mixed in the first zone. Therefore, the sludge was returned from the third zone to the first zone and the sludge in the first zone settles in the bottom. Hence, the five dept meters basins, which the sampling process was limited in a meter from, water level, which affected in less amount of MLSS concentration. In addition, the average MLSS concentration in the second zone and

the third zone of both CASS basins C and D was higher than the first zone because of enough mixing.

From above the passage, the average MLSS concentrations of CASS basins C were higher than D, so the high SV30 values was found in CASS basins C, as illustrated in Figure 4.2.3.

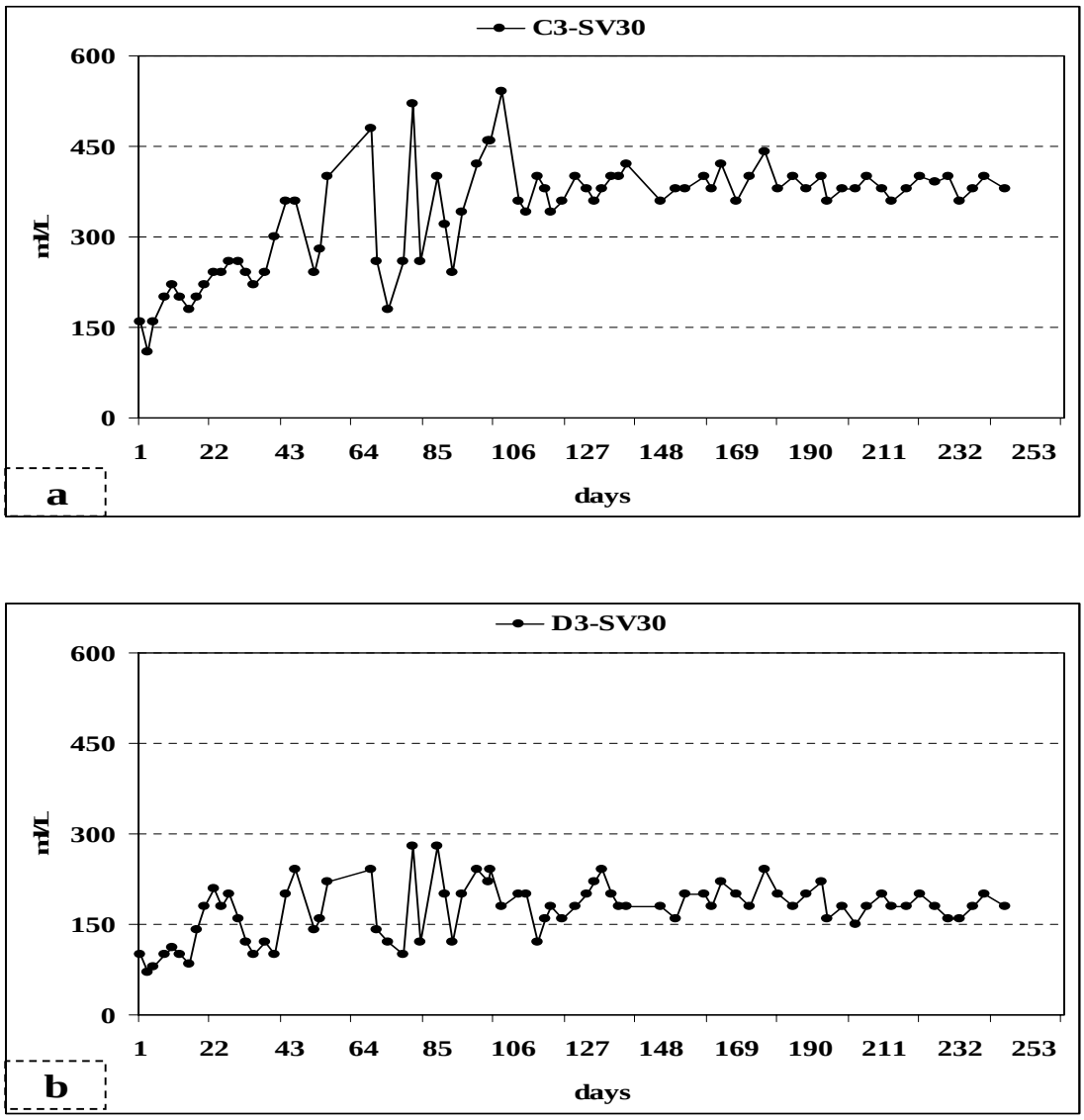


Figure 4.2.3 The SV30 of this study (a) CASS basin C and (b) CASS basin D

COD TKN and phosphorus concentrations of both CASS basins C and D in the first zone were similarly to these in the influent, because of the short HRT (about 1-2 hours) and less reaction. When the influent was pumped to the first zone and rapidly flowed to the second zone, so the parameters in the first zone was similar with influent parameters.

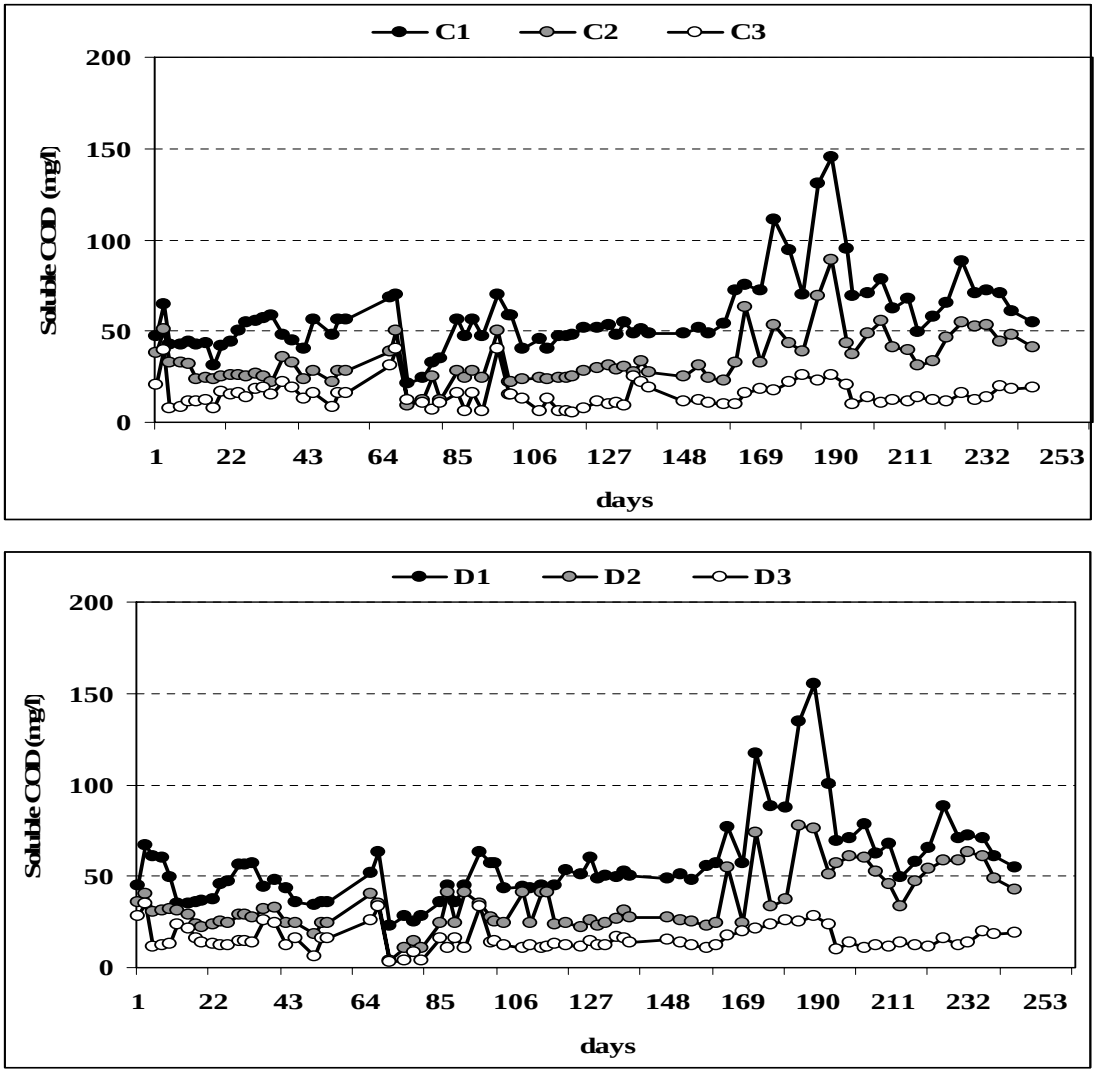


Figure 4.2.4 Soluble COD concentrations in (a) CASS basin C and (b) CASS basin D

The beginning of BPR process may be started in the second zone because the decreasing of the soluble COD and TKN concentrations. The mixing between the influent and sludge in the second zone and substrate was taken up for produce the

energy and new cell. Investigation, the soluble COD concentrations were in the range of 34 -35 mg/l for CASS basins C and D.

The soluble TKN concentrations were in the range of 4.4 and 3.5 mg/l for CASS basins C and D, as illustrated in Figure 4.2.5. Under anaerobic condition, TKN was taken up more and faster, which consistent with the uptake of COD and will be discussed later. The results suggest that nitrogen consumed under anaerobic condition was absorbed while that under aerobic was dissimulator through nitrification with the appearance of nitrate. However, the nitrate-nitrogen concentration of the third zone was about 1 mg/l. Thus, the nitrate interference in anaerobic stage was considerably insignificant and can be ignored. Then, the soluble COD and TKN concentrations in the third zone were decreased like the effluent soluble COD and TKN concentrations.

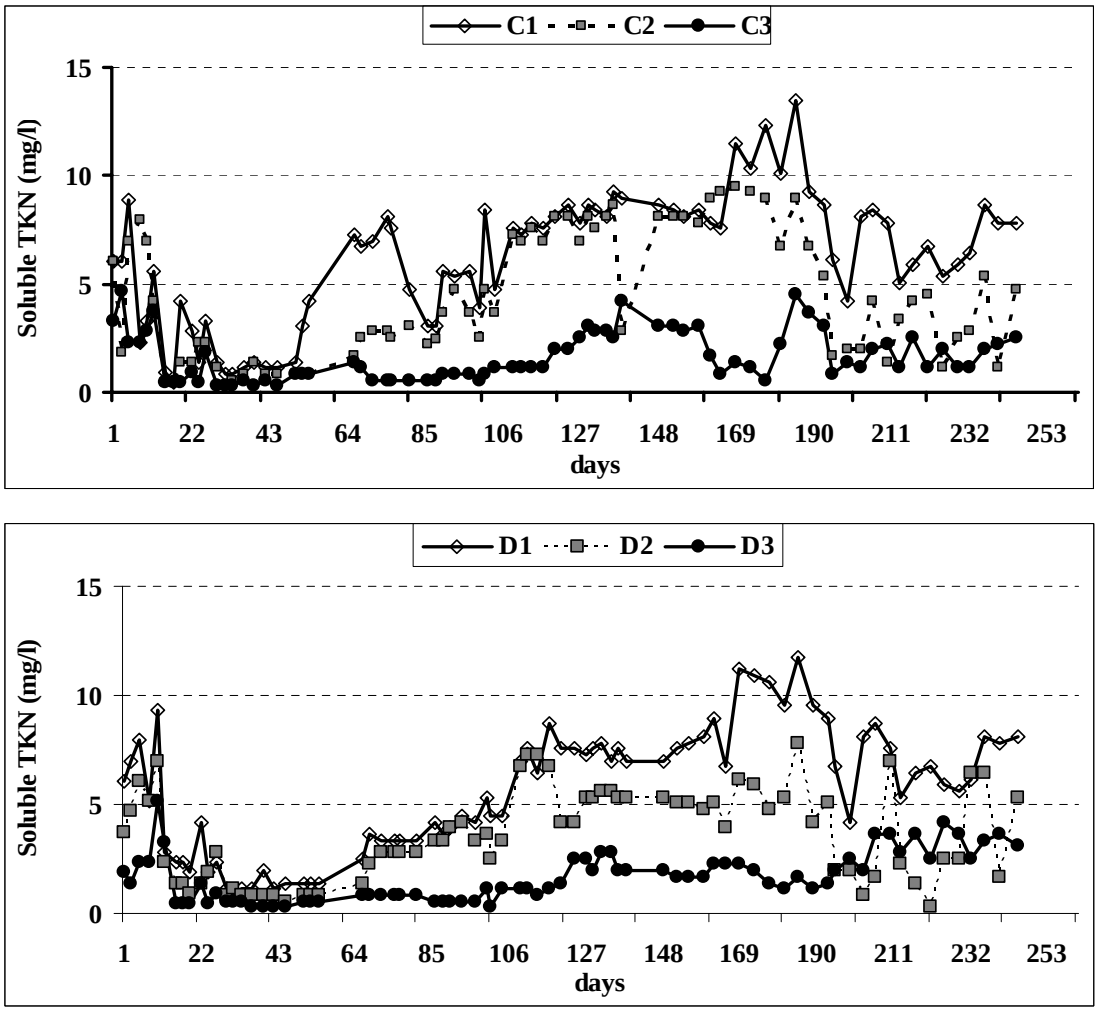


Figure 4.2.5 Soluble TKN concentrations in (a) CASS basin C and (b) CASS basin D

On the other hands, the soluble phosphorus concentrations in each zones different from the soluble COD and TKN concentrations. As a result, the soluble phosphorus concentrations in the second zone were higher than the first zone because BPR process called “P release”, as illustrated in Figure 4.2.6. The last zone is the aerobic zone, so the “P uptake” process occurs in this zone, which the soluble phosphorus concentrations were uptake in biomass. Consequently, the soluble phosphorus concentrations in this zone were in the range of 1-3.1 and 1-3.9 mg/l for CASS basins C and D. The highest %P in biomass for CASS basins C and D were in the range of 2 and 3.5%, respectively. The relationship of the potential in P release and uptake with the %P in biomass indicated that CASS basins D had more potential in P release and uptake than CASS basins C. Therefore, at the end of aerobic condition could accumulate high phosphorus in biomass.

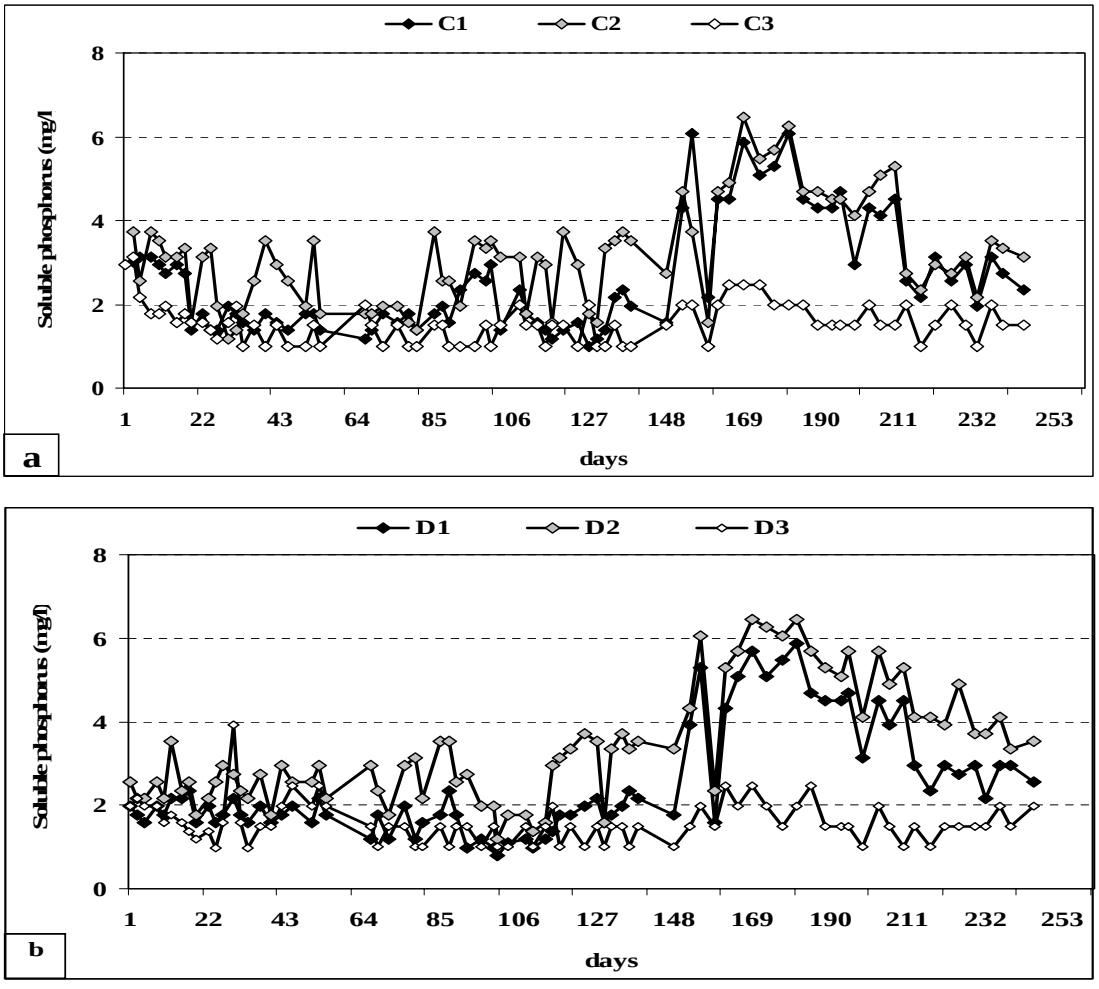


Figure 4.2.6 Soluble TKN concentrations in (a) CASS basin C and (b) CASS basin D

This study the phosphorus release and uptake occurred in the second zone and 3 of both CASS basins C and D. The characteristics for BPR process of CASS basins C and D, as showed in Figure 4.2.7.

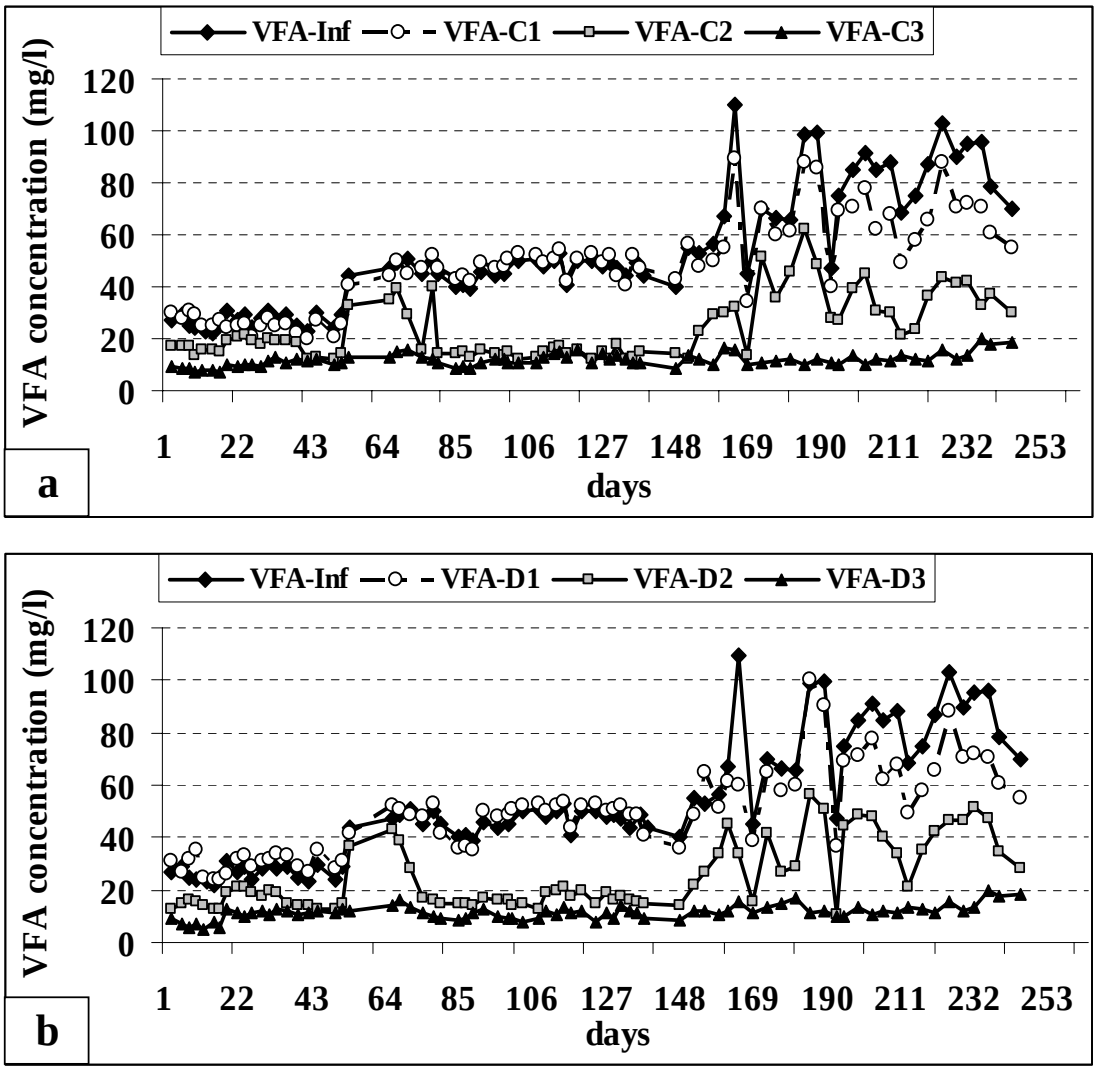


Figure 4.2.7 The VFA concentrations of each zone.

Figure 4.2.7 showed the VFA concentrations in the first zone was similar to VFA concentration of influent. The highest VFA uptake was found in the second zone of both CASS basin C and D. Therefore, VFA uptake concentration was less that affects of influent.

As the result, the VFA uptake concentration of CASS basin D was higher than CASS basin C, so it must have higher energy source for biological phosphorus removal. For that result, phosphorus release and uptake concentration of CASS basin D was higher than CASS basin C.

In this study, the average P release of CASS basin C was lower than D because of the suitable condition in CASS basin D. Interestingly, low DO concentration in the second zone of CASS D about 0.02 mg/l and resulting in the BPR process was better than C. In addition, the VFA uptake of CASS C and D was adjusted. The influent VFA was similarly with C and D, which the occurrence of higher VFA uptake was found in CASS basin D. Therefore, the results of high VFA uptake following to produce high energy and form in term of PHAs kept in cell. Then, the high P uptake was found in CASS basin D depended on high P release in the second zone.

From above the passage could be concluded that the BPR process was occur in this plant. Consideration, the percentage of phosphorus (%P) accumulated in sludge were about 2 and 3.5 % for CASS basin C and D, respectively.

4.3 Effect of temperature and carbon on biological phosphorus removal

This study was to investigate the effects of temperature and carbon feed, which covered low-high temperature and carbon source periods. Thus, the comparison was divided in three cases such as

4.3.1 Case 1, comparison between the first and the second periods, which this case compared in the different temperature and low COD concentration similar of two periods.

4.3.2 Case 2, comparison between the first and the third periods, which this case compared in the similar temperature and different COD concentration.

4.3.3 Case 3, comparison between the second and the third periods, which this case compared in the situation with the different of temperature and COD concentration to investigated the important factor to affect in BPR process.

4.3.1 The comparison effect of temperature and carbon source during the first and the second periods

The effect of temperature and carbon source

The comparisons are parts of the whole investigation in the first and the second periods, which consist of the influent temperature, the influent total COD TKN and phosphorus concentration, the efficiencies of COD, TKN and phosphorus removal and % P in biomass (TSS) as illustrated in Figure 4.3.1. This case was to compare in the different temperature but the influent carbon source was similarly, as illustrated in Figure 4.3.1 a.

This case had the similar of the influent COD concentration, which in the range of 59-63 mg/l that was quite less VFA concentration for BPR process, which was in the range of 49- 52 mg/l as acetic acid. The phosphorus removal efficiency in the second period was higher than the first period. When, consideration the VFA uptake indicated that the higher VFA uptake was occurred in the second period of both of CASS basins C and D. Aerobic phosphorus uptakes of the second periods were increasingly dependent on phosphorus release in the anaerobic zone. It had high capacity for phosphorus uptake and completed P uptake at low temperature (Carucci et al, 1999; Brdjanovic et al., 1997). Therefore, it affected to increase the percentage of PHAs and phosphorus in biomass at low temperature of both CASS basins C and D, as illustrated in Figure 4.3.1 (d). Therefore, the better BPR performance was occurred at low temperature (McClintock et al., 1993, Convertiet al., 1995, Viconneau et al., 1985; Florentz et al., 1987 and Panswad et al., 2003).

This could be said that as the similar of influent COD concentration but the temperature of the second period was lower than the first period, which affected to increase the phosphorus efficiencies of Chongnonsi WWTP. Thus, this case indicated that the temperature must be effect on BPR plant better than the carbon source. However, these did not clearly in the effect of temperature for this case because of the different of temperature only 4°C. Other BPR plants in Australia, England, and Lithuania that the temperature between winter and summer season were different approximately 10°C (Janssen et al., 2002), so it clearly result in the effect of temperature more than BPR plant in Thailand.

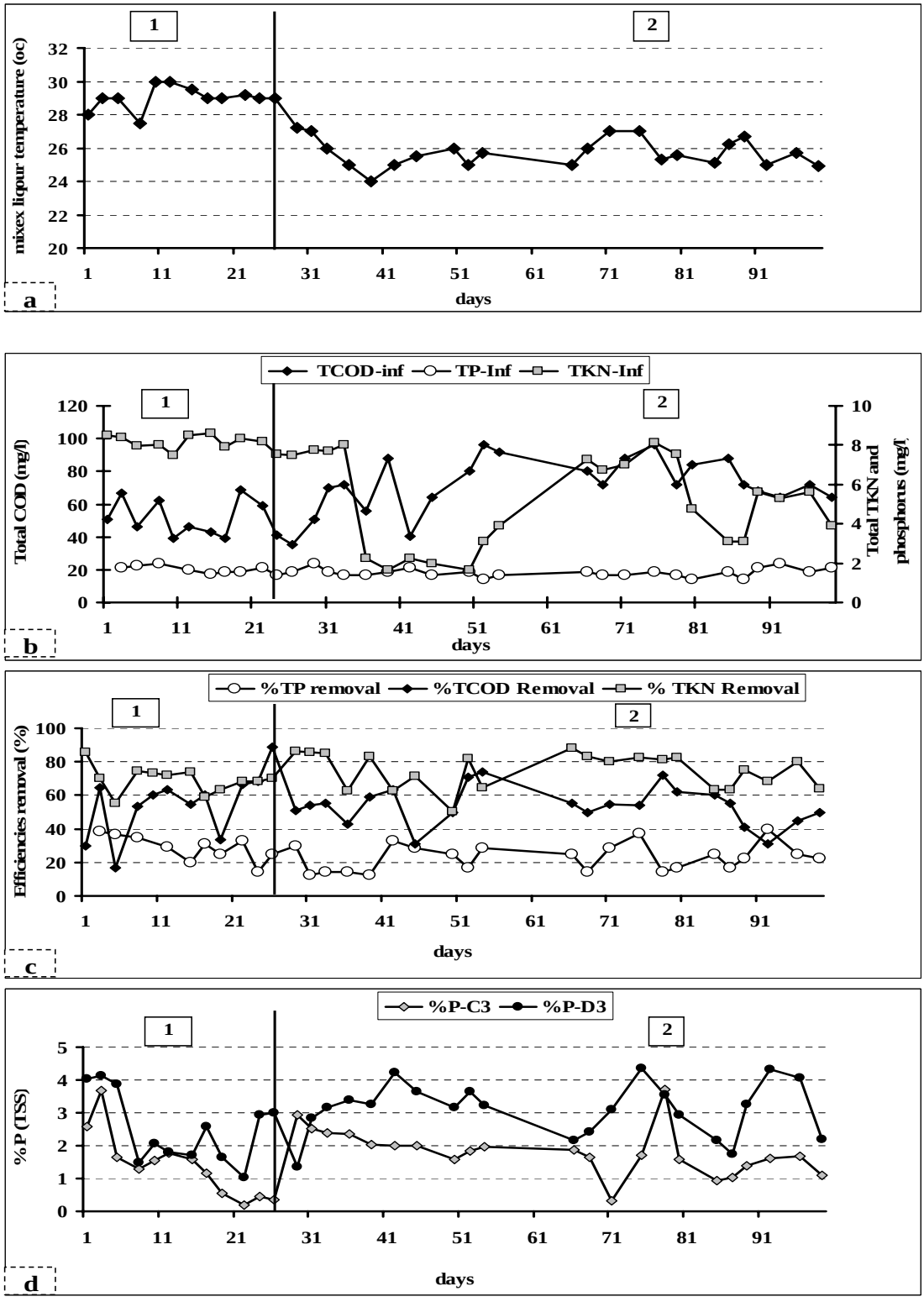


Figure 4.3.1 The comparison between the first and the second period (a) the influent temperature (b) The influent total COD TKN and phosphorus concentration (c) the efficiencies of COD TKN and phosphorus removal and (d) % P in biomass (TSS)

4.3.2 The comparison effect of temperature and carbon during the first period and the third period.

Effect of temperature and carbon source

This case was to compare in the similar temperature but the influent carbon source differed, as illustrated in Figure 4.3.2 a.

Although that, of both periods had similar temperatures (29 and 30 °C), but the phosphorus removal efficiency of the third period was about 57%, which was higher than the first period (about 36%), as illustrated in Figure 4.3.2 c. Consideration, the % PHA and %P (TSS) in biomass of both periods was investigated to show the performance of BPR plant. Figure shows the relation of % PHA and %P (TSS) in biomass, the high of % PHA and %P (TSS) in biomass were found in the third period because this period had enough organic substrate was introduced in the system (Brdanovic;1998, Janssen et al.; 2002).

Figure 4.3.2 b indicated that the influent COD concentration increased from 58 to 97 mg/l in the first and the third periods, respectively. The high influent COD concentration must have high VFA concentration. High VFA concentration in the third period that affected to had high energy to give high anaerobic phosphorus release and high PHA formation in their cells (Brdanovic;1998). Therefore, the increasing of % PHA from in the first to the third periods was 1.4 to 1.6% and 1.7 to 2.2% of CASS basins C and D, respectively. The increasing of % PHA consistent of % P (TSS) in PAOs, which % P (TSS) in the first to the third periods were1.5 to 2.1% and 2.8 to 3.3% of CASS basins C and D. The high % PHA formation in their cells and promote of the high of % P (TSS) in biomass was found in the third period, as illustrated in Figure 4.3.2 d.

From above the passage indicated that similar temperature of both periods with the different influent COD concentrations indicated that at high influent COD concentration must had high VFA concentrations. Therefore, high VFA concentrations were enough energy and substrate for BPR process. Thus, this case the important factor that could effect on biological phosphorus removal was influent carbon concentration more than temperature.

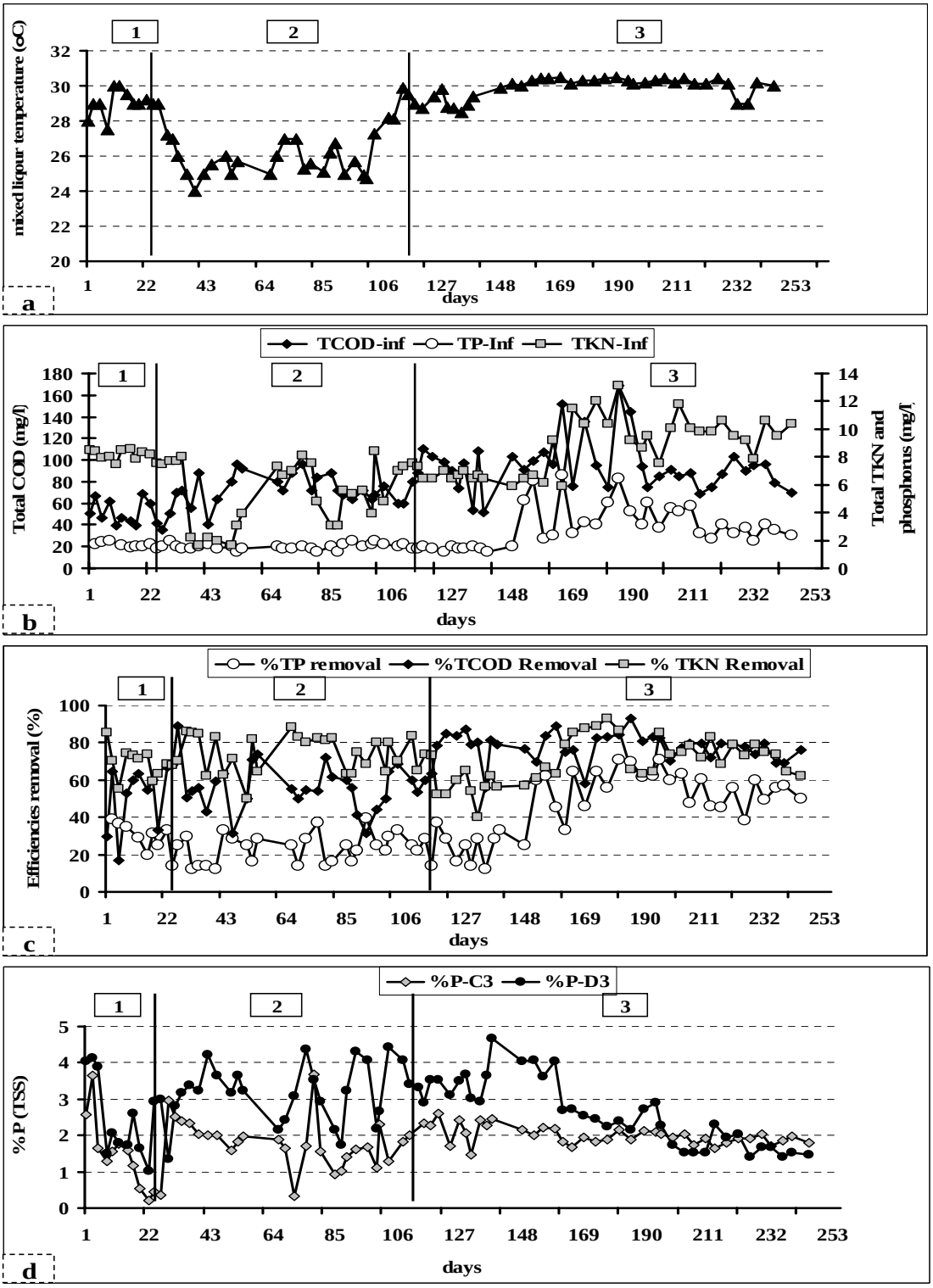


Figure 4.3.2 The comparison between the first and the third period (a) the influent temperature (b) The influent total COD TKN and phosphorus concentration (c) the efficiencies of COD TKN and phosphorus removal and (d) % P in biomass (TSS)

4.3.3 The comparison effect of temperature and carbon during The second period and the third period.

Effect of temperature and carbon source

This case was to investigate the different of both temperature and carbon source on biological phosphorus removal. The phosphorus removal efficiency and better BPR performance must be occurrence in low temperature. Although, the lower temperature was found in the second period but the influent COD concentration less than the third period, as illustrated in Figure 4.3.3 b. Therefore, the phosphorus removal efficiency of the third period increased to 57% whereas the temperature higher than the second period, as illustrated in Figure 4.3.3 b. As a result, the influent COD concentration of the third period increased to 97 mg/l and resulting to VFA concentration increased which enough carbon sources to BPR process and produced new cell.

The high VFA concentration in the influent wastewater in the third period must be available, which induce the phosphate-removing bacteria to take up the acids and release phosphate into solution (Morse et al., 1998). In the aerobic phase, luxury P-uptake occurs higher than the first and the secondary periods. The % PHA and % P in biomass (TSS) in the third period was higher than the second period, which consistent with the amount of P release and uptake in BPR process. The VFA uptake in the second period had lower than the third period of both CASS basins C and D, which was only 25 mg/l while the second period were 9 and 13 mg/l, respectively. Therefore, in this part COD:TP ratios was used to investigated effect of carbon source on BPR system.

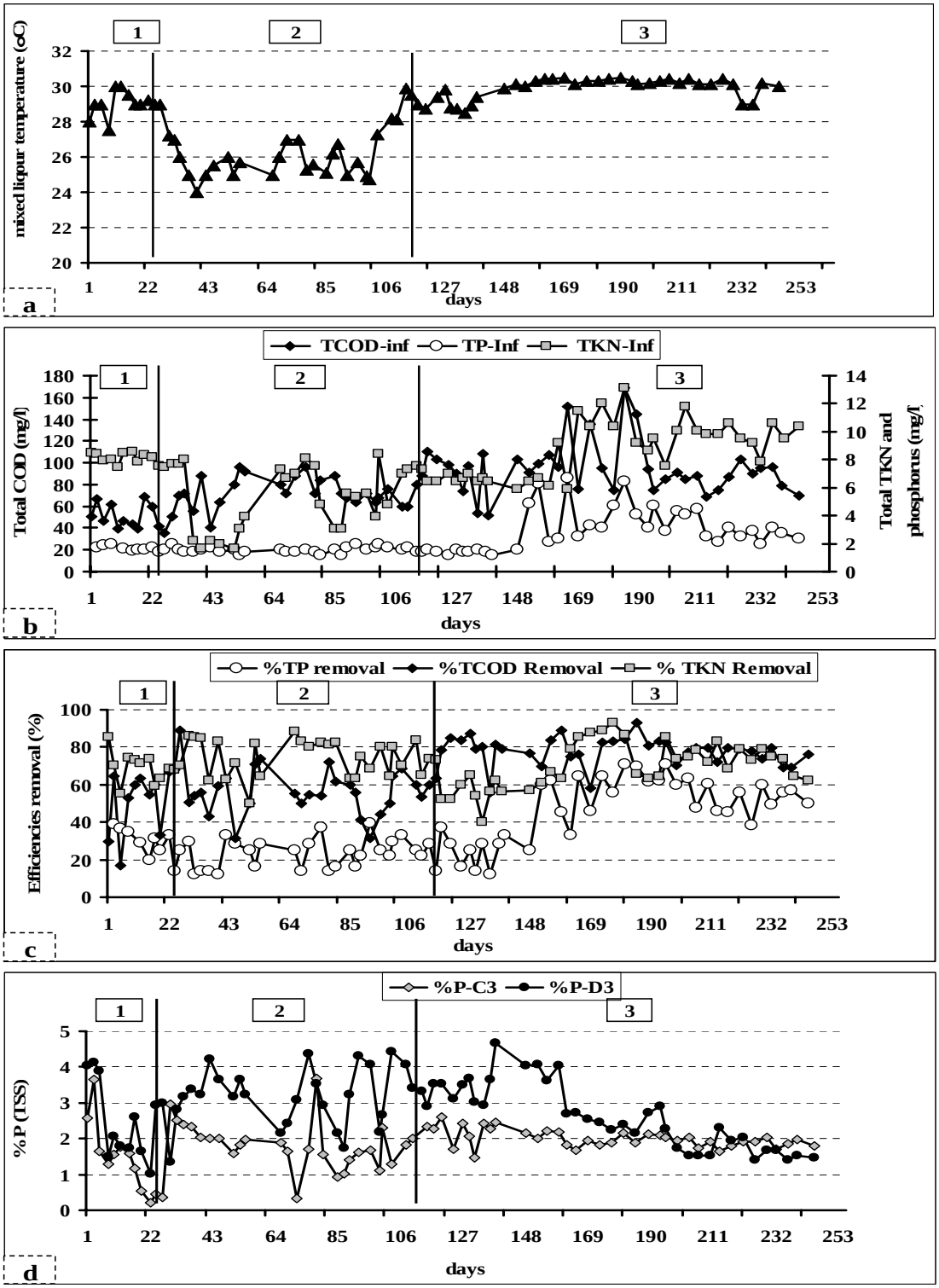
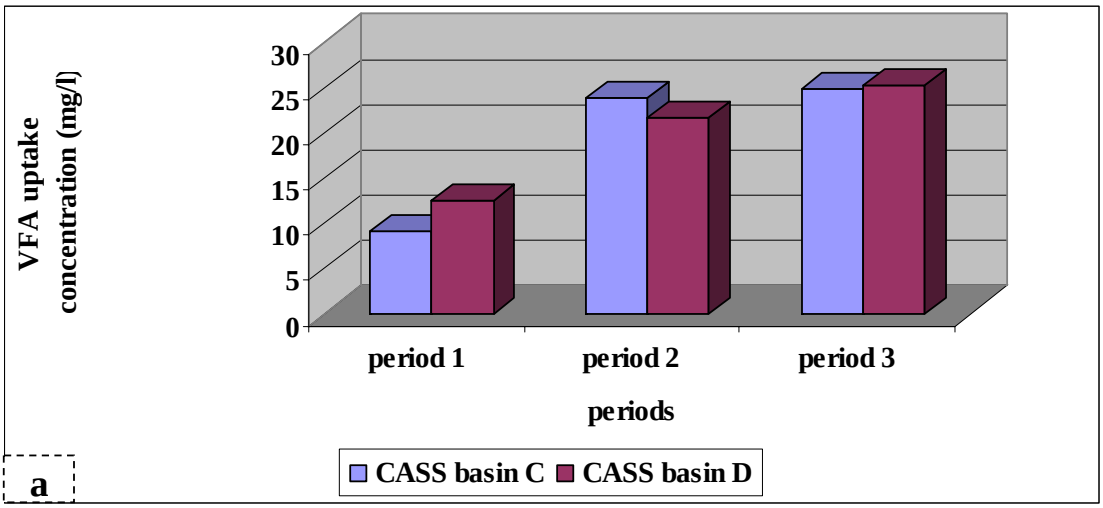
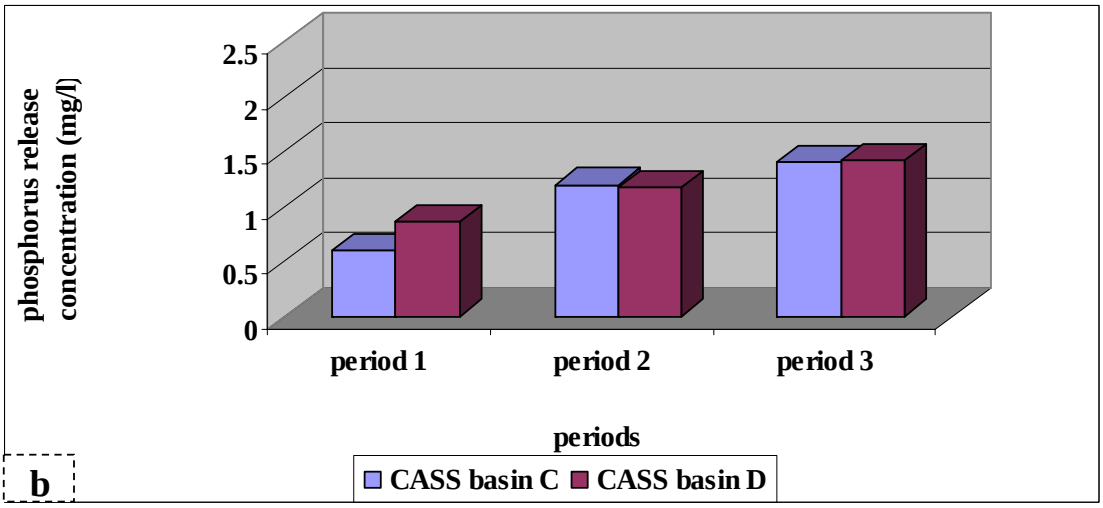


Figure 4.3.3 The comparison between the second and the third period (a) the influent temperature (b) The influent total COD TKN and phosphorus concentration (c) the efficiencies of COD TKN and phosphorus removal and (d) % P in biomass (TSS)

Hence, the carbon source effected on BPR process by the consideration in term of VFA uptake, phosphorus release and uptake concentration. As the result, the CASS basins C had consistent as same as CASS basins D that the low in low carbon periods affected on decrease of the biological phosphorus removal, which the result of low VFA uptake, phosphorus release and uptake concentration. On the other hands, the high carbon periods affected on increase the biological phosphorus removal that the results of high VFA uptake, phosphorus release and uptake concentration. The VFA uptake, phosphorus release, uptake concentration and % P (TSS) in three periods, as illustrated in Figure 4.3.4 and Figure 4.3.5.





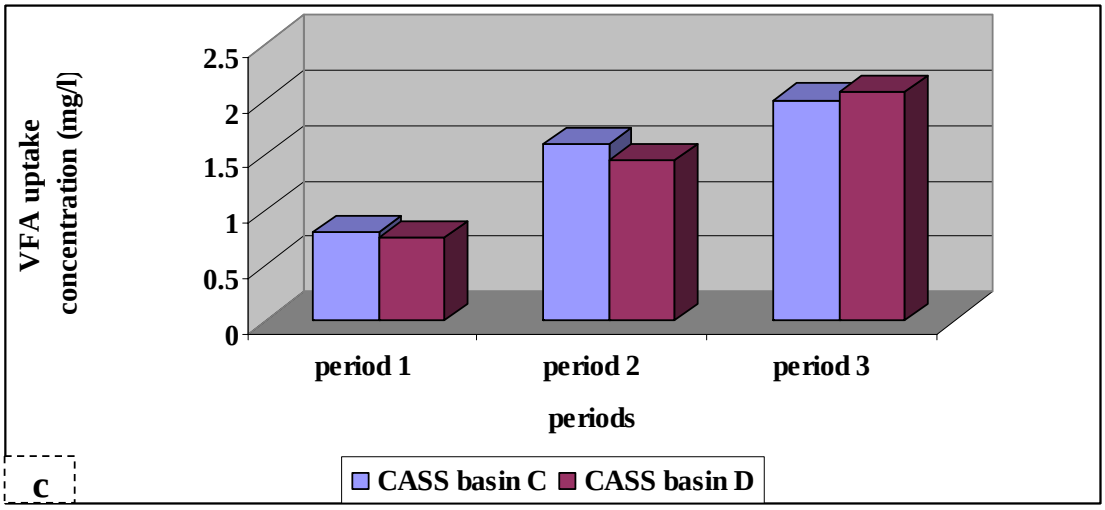


Figure 4.3.4 The performance of CASS basins C and D of three periods in term of (a) VFA uptake (b) phosphorus release and (c) phosphorus uptake

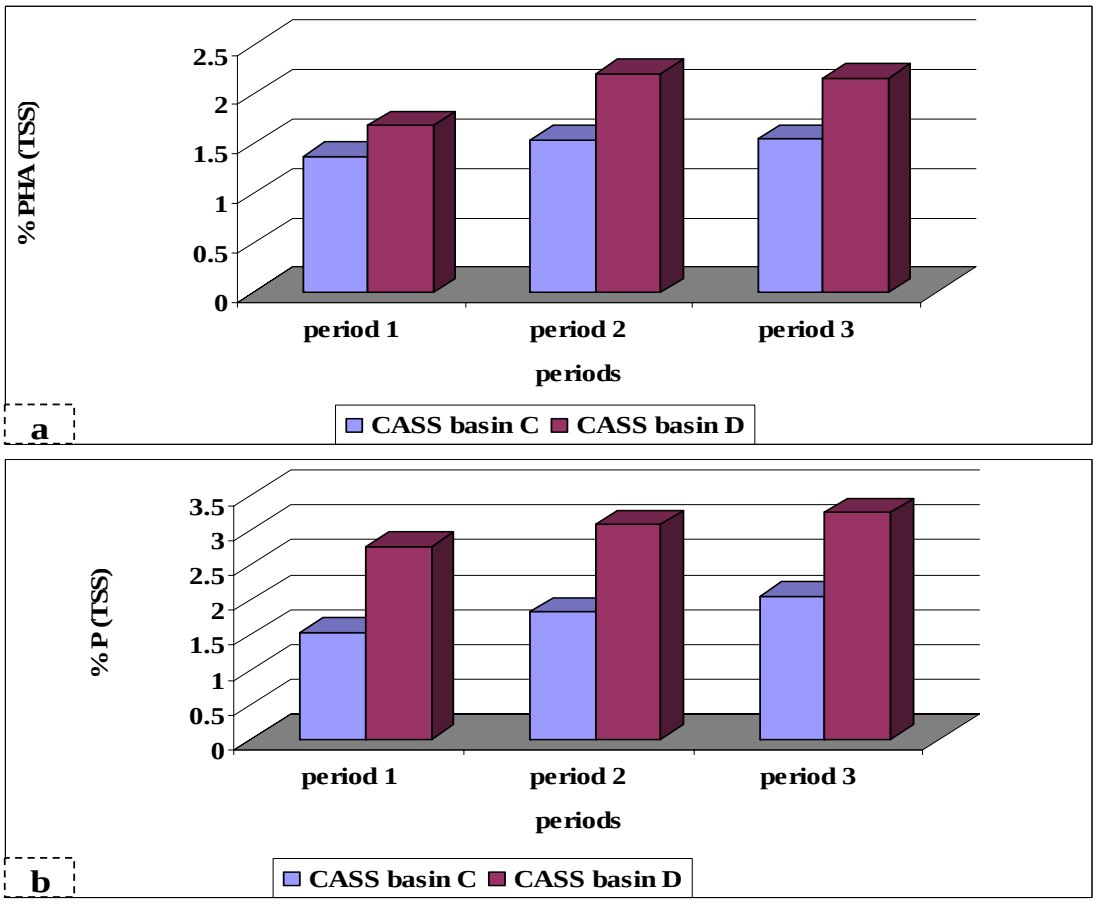


Figure 4.3.5 The performance of CASS basins C and D of three periods in term of (a) %PHA (TSS) (b) % P in biomass(TSS)

Table 4.3.1 The average COD:TP ratios in each periods.

Periods	COD:TP	BOD:TP
1	35:1	21:1
2	39:1	30:1
3	32:1	22:1

Table 4.3.1 shows the COD:TP and BOD:TP ratios of each periods, which the average COD:TP ratios of three periods were about 35:1, 39:1 and 32:1. BOD:TP ratios of three periods were about with the phosphorus removal efficiency were about 36, 39 and 57%, respectively. (COD:TP ratios of other plants showed in Appendix E)

Table 4.3.1 shows the P release: P uptake ratios which the third period had highest ratios were about 1.4 and 1.8 for CASS basin C and CASS basin D, respectively. In the third period had highest P release: P uptake ratios because had lowest COD:TP ratio was about 32:1 which the first period and the second period had COD:TP ratios were 35:1 and 39:1, respectively. The lowest COD:TP ratio affected to have the highest VFA uptake, P release, P uptake, and % P in biomass (TSS). As a result, it could affect to increase the efficiency phosphorus removal.

In addition, COD:TP ratios of the first and the second periods were higher than the third period with COD/TP ratio was 32:1. Therefore, the VFA uptake, P release, P uptake and % P (TSS) in biomass were higher than the first and the secondary periods. Consequently, the COD:TP ratios related with % P in biomass (TSS) that at lower COD:TP ratios would have high % P in biomass (TSS) (Punrattanasin, 1997).

P uptake: P release ratio of the third period of CASS basin C and CASS basin D were 1.4 and 1.8 which higher than the first and the secondary periods were 1.3 and 0.9, respectively. Then, COD:TP in the third period decreased which consistent with P uptake:P release ratio increased affected of the efficiency phosphorus removal increased to 57%.

In addition to considered P release: P uptake ratios indicated that at the third period had highest ratios were about 1.4 and 1.8 for CASS basin C and CASS basin D, respectively. In the third period had highest P release: P uptake ratios because had lowest COD:TP ratio was about 32:1 which the first and the second periods had COD/TP ratios were 35:1 and 39:1, respectively. The lowest COD:TP ratio affected

to have the highest VFA uptake, P release, P uptake, and % P in cell and affected to increase the efficiency phosphorus removal. A reduction in BPR can also occur with high influent COD:P ratios. If the COD is not totally sequestered in the anaerobic zone, residual substrate remains to support the growth of filamentous bacteria in the oxic zone (Chang et al., 1996 and Furumai et al. 1999).

Consequently, COD:TP ratios of Chongnonsi WWTP were in range 32-39. It was quite lower than other WWTP. The COD:TP ratios in the first and the third periods of Chongnonsi WWTP was close to COD:TP ratios of Elburg WWTP, which it was about 30:1 but the efficiency of phosphorus removal was 95% (Janssen, et.al. 2006). COD:TP ratios in the secondary period was 39:1, it was close to COD:TP ratios of Haarlem Waaederpolder WWTP that was about 40:1 that the efficiency of phosphorus removal was 88% (Janssen, et.al. 2006).

Panrattanasin (1997) and Janssen, et.al.(2006), who reported the COD:TP ratios increased, the % P in sludge decreased.

Many BPR plants in Lithuania, i.e., Vilnius, Klaipeda, Alytus, Siauliai and Utena WWTPs, found that the efficiency of phosphorus removal increased when temperature decreased (Vabolienc.G, Matuzericius.A.B. and Daukneys.R. 2007). The confirmation of the effect of temperature used the %P in biomass (TSS). Hence, the average of %P in biomass (TSS) of the secondary period was about 1.8 and 3.1% for CASS basins C and D while the first period was about 1.5 and 2.8%, respectively.

Transition state

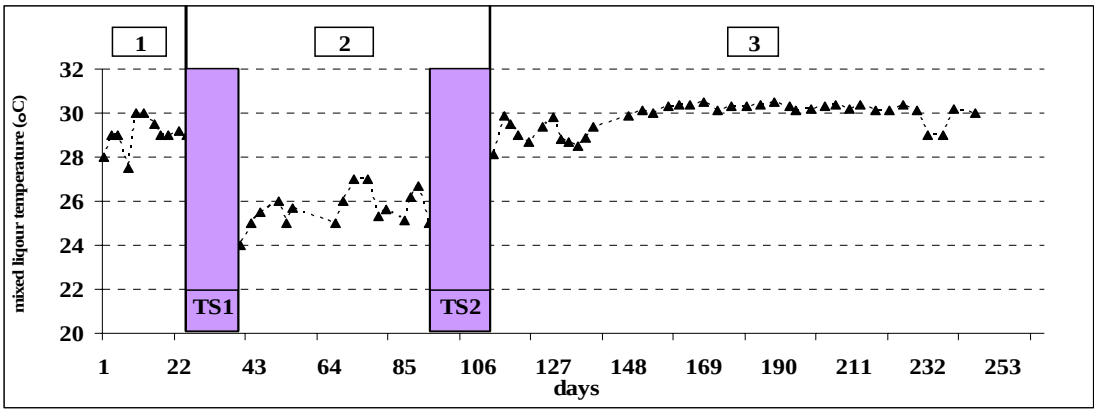


Figure 4.3.6 Transition state of this study.

Figure 4.3.6 indicated that the temperature from the days 27 to 38 was decreasing to about 25 °C which about 11 days. The period was call “transition state”

which the other transition state was from the day 101 to 112 with temperature was increasing to about 30 °C.

Transition State 1 (TS 1)

The temperature in this period was decreased to 25 °c which it into winter season. This period had about 11 days which from the days 27 to 38. VFA uptake in this period was slightly higher than the first period. Then anaerobic phosphorus release and phosphorus uptake was higher than the first period depend on the temperature decreased (Converti et al., 1995). The phosphorus removal efficiency of TS 1 was lower than the first period but lower than the secondary and the third period.

Transition State 2 (TS 2)

The temperature in ST 2 was increased to 30 °c which it into summer and rain season. This period had about 20 days which from the days 90 to 110. VFA uptake in this period was lower than the first, the second and the third periods. Then anaerobic phosphorus release and phosphorus uptake was lower than of all periods depend on the temperature increased (Converti et al., 1995).

Sub conclusion

As a result, both temperature and carbon feed were affected on biological phosphorus removal. Therefore, at the difference temperature values but similar COD concentrations indicated that the BPR performance was better at low temperature. Then, at the difference COD concentrations but similar temperature values indicated that at high COD concentrations periods showed the better BPR performance.

However, the different temperature values between low and high temperature were about 4 °C, which may be not obvious the effect of temperature. Therefore, other countries in Europe that more different temperature values between low and high temperature, so could show the clearly result in effect of temperature more than Thailand. This study, Chongnonsi WWTP operated in low temperature with COD concentrations in the range of 59-63 mg/l indicated that moderate BPR performance was found in high temperature values. However, in the last period the plant was in high temperature values operating and the efficiency of phosphorus removal increased. As a result, influent nitrate concentration approximate nil and nitrate in the return sludge from the third to the first zones, which it was a little and did not affected on BPR process (von Sperling M. and de Lemos Chernicharo C.A., 2005). However, the comparison the effluent phosphorus concentration between the operations was AS and CASS configurations found that the effluent phosphorus concentration in CASS configurations (about 1.2 mg/l) was lower than AS configuration (about 2.0 mg/l) and illustrated in Appendix I. Therefore, the operation in CASS configuration occurrence in the better biological phosphorus removal than AS configuration and did not affect on BPR performance.

Consequently, the important effect on BPR performance is carbon source than temperatures. The enough carbon sources for biological phosphorus removal and could confirm the result in Part II of SBR reactors, which explained in next part.

4.4 Part II SBR Reactors

This experimental part was conducted by using SBR reactors to investigated effects of temperature and low carbon feed on biological phosphorus removal. Two temperature controllable reactors were used in this study (as called R1 and R2 reactors), and operated in the laboratory of Department of Sanitary Engineering, Mahidol University. From the first part, the results illustrated that there was very weak biological phosphorus removal occurred in the Chongnonsi WWTP. Some presumptions could be drawn from the results, i.e., the operating temperature in Chongnonsi WWTP was too warm for BPR occurrence, too low COD and phosphorus loadings in the fed wastewater, or CASS operating might not be proper to BPR, or all of them. Therefore, this experimental part composed of five consecutive phases in order to investigate those presumptions one by one as listed in Table 4.4.1.

The first is 'Acclimatization phase', which aimed to stimulate good biological phosphorus removal, therefore, synthetic wastewater containing 300 mg COD/l (from acetic acid 220 mg COD/l and nutrient broth 80 mg COD/l) and 20 mg/l phosphorus was fed into those two reactors. Both reactors were operated at constant temperature of 20^{o}C until they reach a steady state.

The second the first phases to investigate the effect of temperature increase on BPR efficiency by gradually adjust operating temperature in the reactor R2 from 20 to 30^{o}C with the rate of not more than 0.5^{o}C/day. The same synthetic wastewater as used in the previous phase was still fed into both reactors. Therefore, the reactor R1 was continued the same operation to the first phase. In this phase, when the steady state was reached, the temperature effect on BPR was determined by making a comparison between the reactors R1 (20^{o}C) and R2 (30^{o}C).

The third the first phases to investigate the effect of CASS-like operation on BPR efficiency. The operating conditions similar to those of CASS system in the Chongnonsi WWTP were applied in this phase, such as HRT, SRT, cycle time, etc., detail as previously described in Chapter III. The same synthetic wastewater was still fed into both reactors during this phase.

The fourth the first phases the preparation for using real domestic wastewater in the last phase. The same operating conditions were continued after the third phase. The

synthetic domestic wastewater with COD and phosphorus concentrations similar to real domestic wastewater was synthesized and fed to both reactors. The effect of small loadings in synthetic domestic wastewater was evaluated when the steady state was reached.

In the last phase, real domestic wastewater of the Chongnonsi WWTP was used in order to determine their effect on BPR efficiency.

Table 4.4.1 A list of five consecutive phases conducted in this part.

Phases	Condition	Wastewater	Days of operation	Temperature (°C)	
				R1	R2
1	Acclimatization	Synthetic wastewater	1 - 87	20	20
2	Increase temperature	Synthetic wastewater	88 - 164	20	30
3	Changing operation to CASS	Synthetic wastewater	165 - 195	20	30
4	CASS operation	Synthetic domestic wastewater	196 - 220	20	30
5	CASS operation	Real domestic wastewater	221 - 256	20	30

4.5 Characteristics of synthetic wastewater, synthetic domestic wastewater and real domestic wastewater

Synthetic wastewater

This wastewater was used in the first to the third phases. The average characteristics of synthetic wastewater consisted of COD, TKN and TP concentrations in the ranges of 296-361 mg/l, 10-12 mg/l and 14-22 mg/l, respectively, corresponding to COD:TP ratios in the range of 16-21 as illustrated in Table 4.5.1. Nitrate was not added in this synthetic wastewater and was found to be nil.

Table 4.5.1 Characteristics of wastewaters used throughout this experimental part (Part R2)

Phases	Wastewater	COD	TKN	TP	COD/TP
1-3	Synthetic wastewater	296-360	10-12	14-22	16-21
4	Synthetic domestic wastewater	84-110	7.5-8.4	3.1-4.4	25-27
5	Real domestic wastewater	85-104 (SCOD 43-74)	6.7-8.6	2.9-4.4	24-29

Synthetic domestic wastewater

This wastewater was used in the fourth phase to imitate the real domestic wastewater, which containing lower COD and phosphorus concentration than the previous synthetic wastewater. The average characteristics of synthetic domestic wastewater used in this phase consisted of COD, TKN and TP concentrations in the ranges of 84-110, 7.5-8.4 and 3.1-4.4 mg/l, respectively, corresponding to COD:TP ratios in the range of 16-21.

Real domestic wastewater

Real domestic wastewater was collected from the effluent of primary treatment of Chongnonsi WWTP. During the investigation in this phase, the average characteristics of real domestic wastewater consisted of COD, TKN and TP concentrations in the ranges of 85-104, 6.7-8.6 and 2.9-4.4 mg/l, respectively. Soluble COD was also determined and in the range of 43-74 mg/l, corresponding to COD: TP ratios in the range of 24-29.

Seed sludge

Seed sludge used in this experimental part was taken from CASS reactor of Chongnonsi WWTP. Phosphorus contents in this seed sludge were in the range of 1-2% P of TSS. Both reactors (R1 and R2) were fed with the seed sludge concentration of 4,000 mg/l. The appearance of seed sludge was described in Table 4.4.2.

Table 4.5.2 The appearance of seed sludge used in this experimental part (Part R2)

Parameter	Appearances
Color	Dark brown
Odor	Likely soil smell
%P	1-2%

4.6 Performances of SBR System during acclimatization Period

4.6.1 Performance of SBR Systems

The experiment started with seeding and acclimatization of sludge biomass that was obtained from the excess sludge tank of Chongnonsi WWTP. The initial mixed liquor suspended solids (MLSS) concentration was about 4,000 mg/l and was maintained around 3,500 mg/l after operating for some time. During seeding and acclimatization period, two SBR systems were fed with COD concentrations increase from 25, 50, 75 to 100% of designated COD concentration of 300 mg/l.

The efficiency of COD, TKN, and phosphorus removal of both R1 and R2 summarized and as illustrated in Table 4.6.1. The first phase was found to perform the highest treatment efficiency, while the lowest was found in the fourth phase and the fifth phase.

Table 4.6.1 The efficiencies of COD, TKN and TP removal of R1 and R2

Reactors	Parameters	Percentage Removal Efficiency				
		The first phase	The second phase	The third phase	The forth phase	The fifth phase
1	COD	97	96	95	87	88
	TKN	86	87	84	83	70
	TP	95	94	93	63	64
2	COD	97	94	94	83	84
	TKN	86	84	81	59	70
	TP	95	87	86	57	51

COD concentrations

COD concentration of synthetic wastewater was prepared in the range of 300-330 mg/l, which composed of acetic acid and nutrient broth. The efficiencies of COD removal in the first through the fifth phases were 96, 95, 91, 85 and 82% for R1, respectively and were 95, 93, 85, 80 and 79% of R2, respectively. Profiles of COD concentration and removal efficiency were shown in Figure 4.6.1.

COD concentrations at the end of anaerobic condition throughout the whole study were in the range of 19-24 and 20-26 mg/l of reactor R1 and R2, respectively. While, those at the end of aerobic condition were in the range of 10-12 and 11-17 mg/l of R1 and R2, respectively.

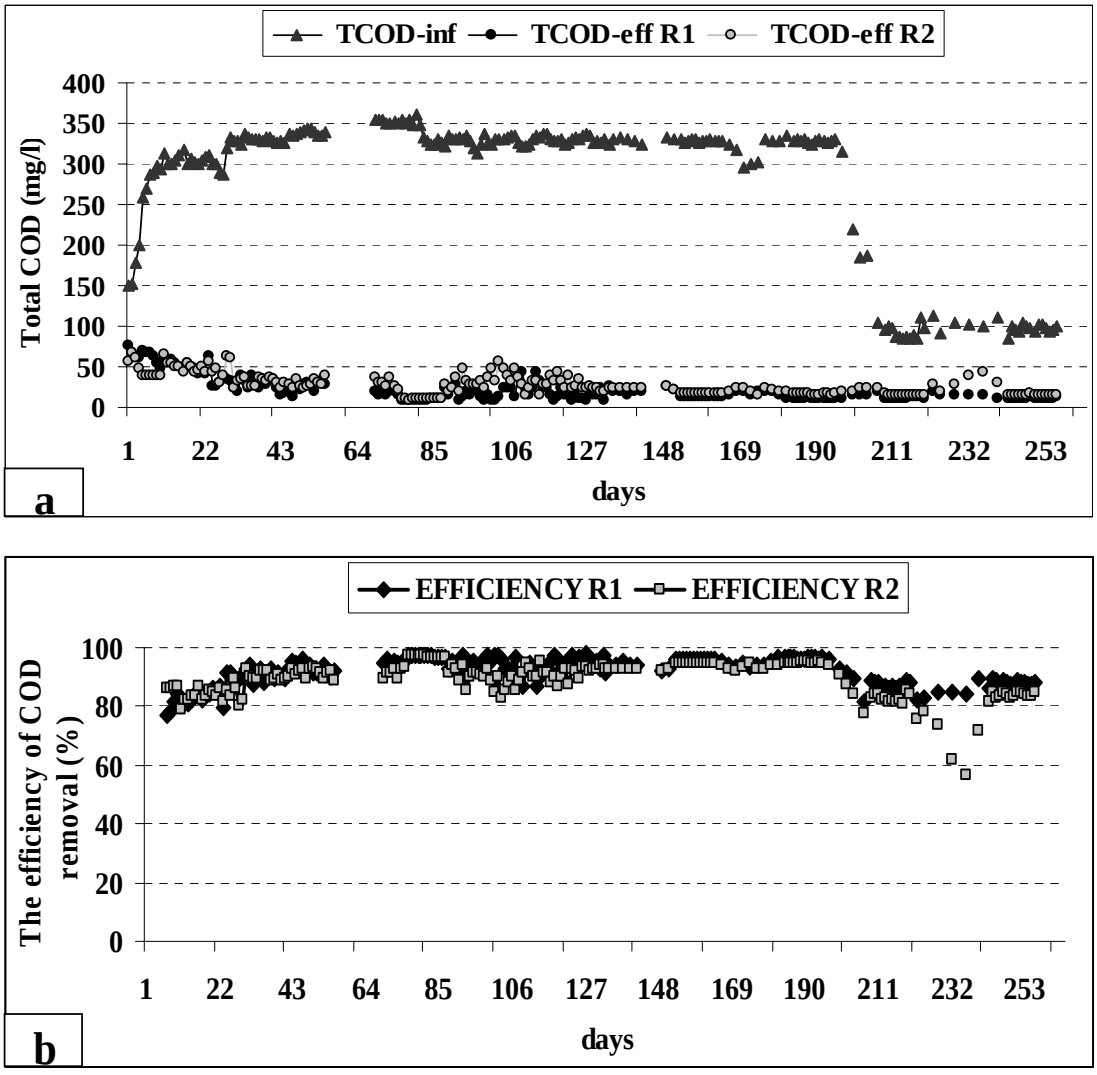


Figure 4.6.1 COD concentrations profile of five phases (a) COD concentrations profile of all condition (b) The efficiencies of COD removal (%)

VFA concentrations

In this study, acetic acid and nutrient broth were used as carbon sources for microorganism. The synthetic wastewaters contained VFA concentrations around 200-220 mg COD/l (during the first to the third phases) and were about 40 mg COD/l during the forth and fifth phases, as illustrated in Figure 4.6.2. VFA concentrations rapidly decreased since anaerobic condition, concurrently with phosphorus release, illustrating that there was PAOs activity.

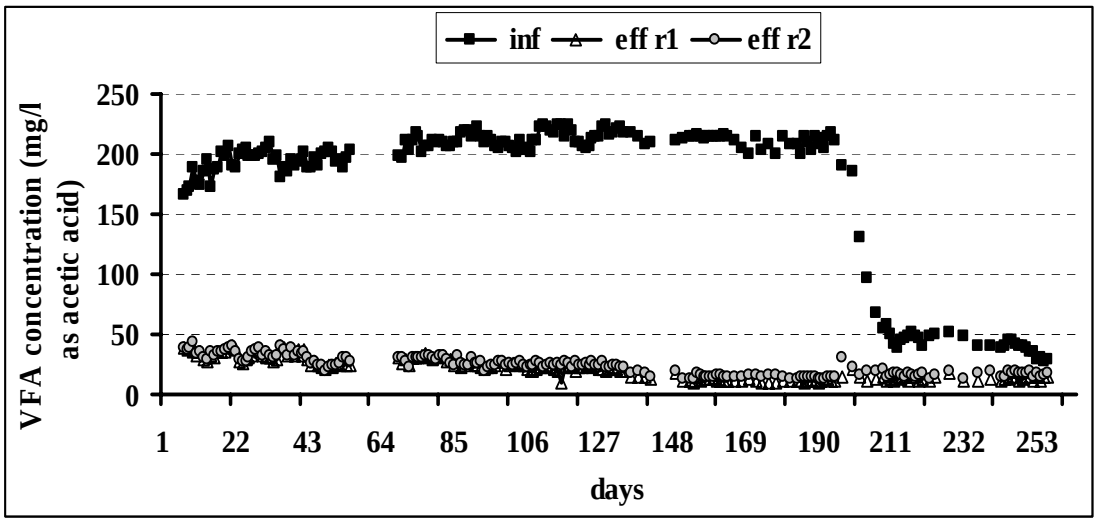


Figure 4.6.2 VFA concentrations profile of five phases

TKN concentration

This study was to investigate the effect of temperature and low carbon on BPR performance, therefore the synthetic wastewater used in this study contained nitrogen only enough for cell synthesis. The average of influent TKN concentration was about 11 mg/l during the first to the third phases. TKN concentrations at the end of anaerobic condition were in the range of 2.7-4.9 mg/l and 3.0-6.6 mg/l for R1 and R2, respectively. The effluent of TKN concentrations were in the range of 2.7-4.9 mg/l and 3.0-6.6 mg/l for R1 and R2, respectively. As well as, TKN removal the efficiencies of

were 86, 87, 84, 72 and 73% for R1. As well as it average 86, 84, 81, 60 and 53% of R2 for five phases as illustrated in Figure 4.6.3.

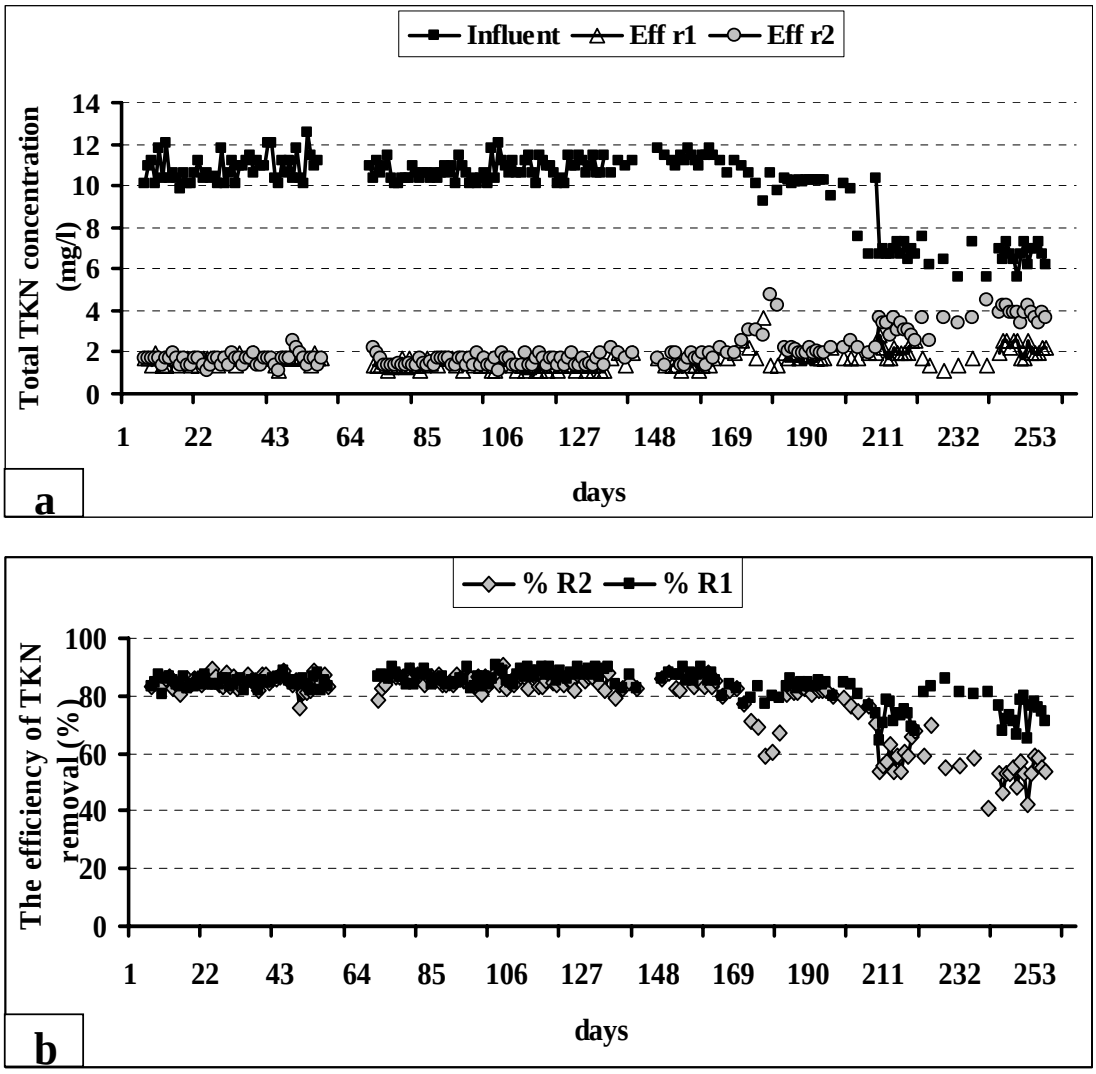


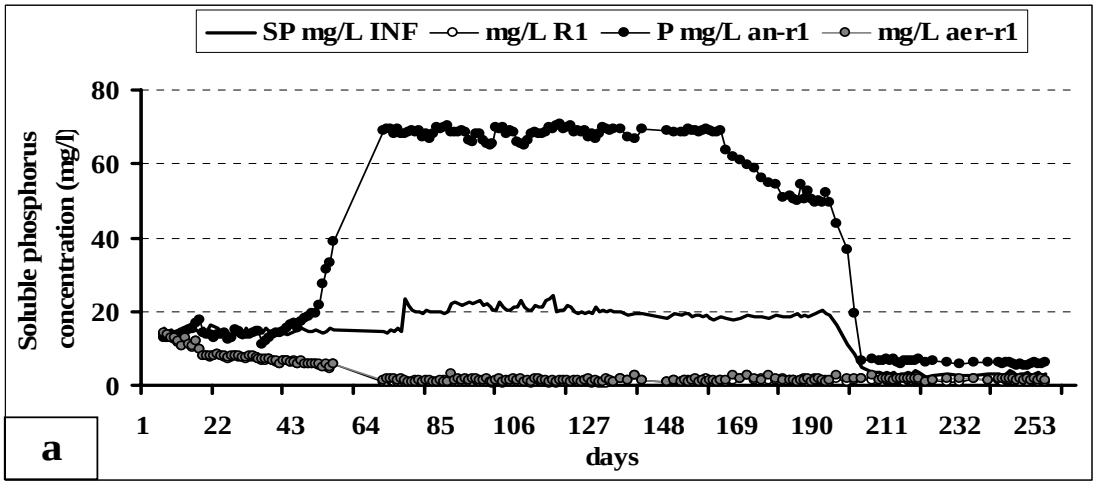
Figure 4.6.3 TKN concentrations profile of five phases (a) TKN concentrations profile of all condition (b) The efficiencies of TKN removal (%)

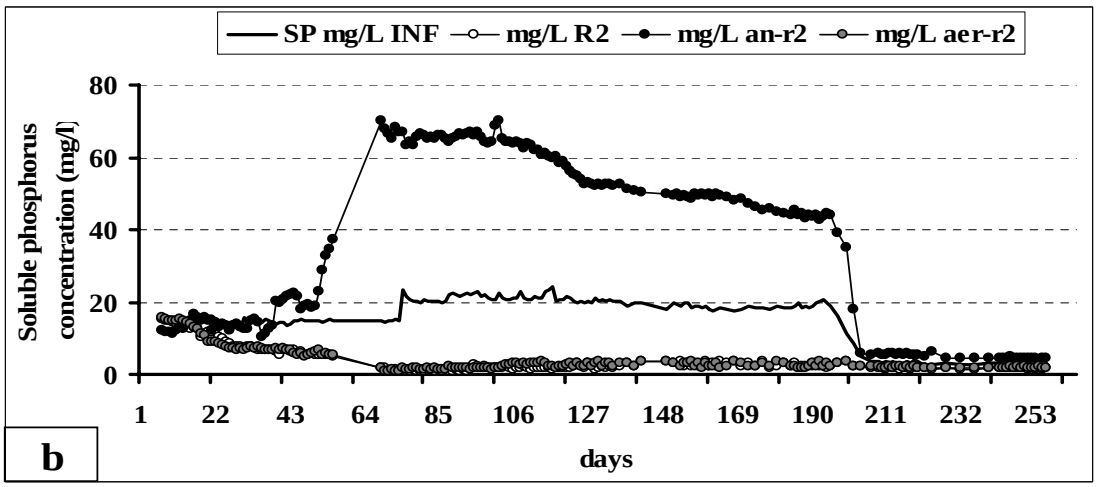
Phosphorus concentration

The profile of phosphorus concentrations in the influent, anaerobic condition, aerobic condition and the effluent of both R1 and R2 as illustrated in Figure 4.54. The influent phosphorus concentrations were about 20 mg/l for the first to the third phases. During the fourth phase, influent phosphorus concentrations were decreased to about 3

mg/l, in order to be similar to those averagely contained in real domestic wastewater used in the fifth phase of this study. The phosphorus concentrations in anaerobic condition of R1 and R2 during the first phase through the third phase were in the range of 51-68 mg/l and 44-65 mg/l respectively, while the anaerobic phosphorus concentrations of R1 and R2 during the fourth and fifth phases were in the range of 18-19 mg/l and 14-17 mg/l, respectively. As a result, there was phosphorus release occurred in anaerobic condition of every phase, it was quite high during the first phase and gradually reduce to since the second through the fifth phases.

As a result, the efficiencies of phosphorus removal in the first phase through the fifth phases were 95, 93, 90, 63 and 59% for R1, respectively. As well as, they were 95, 85, 82, 59 and 45% for R2.





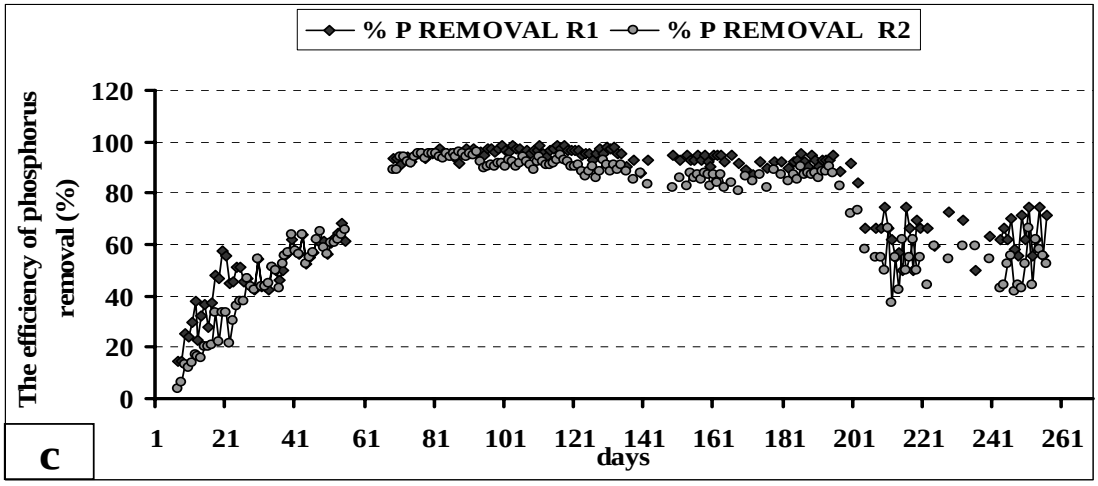


Figure 4.6.4 Phosphorus concentrations profile of five phases (a) phosphorus concentrations profile of all condition in R1 (b) phosphorus concentrations profile of all condition in R2 (c)The efficiencies of COD removal (%)

MLSS concentration

The initial MLSS concentration of seed sludge fed into R1 and R2 were approximately 4,000 mg/l and were maintained above 3,000 mg/l in R1 and above 2,000 mg/l in R2 as shown in Figure 4.5.5. During acclimatization phase, both reactors were operated at 20 °C mixed liquor in both reactors appeared as light brown floc. When the reactor R2 was operated at room temperature (about 30°C), it was found that the mixed liquor turn dark brown than those at 20 °C operation with large floc. In addition, MLSS concentration of R1 was a little higher than that of R2 during the second phase, resulting in less SV_{30} and SVI than those in R2 because of effect of temperature (Dungjai, 2000; Krishna and van Loosdrecht,1999).

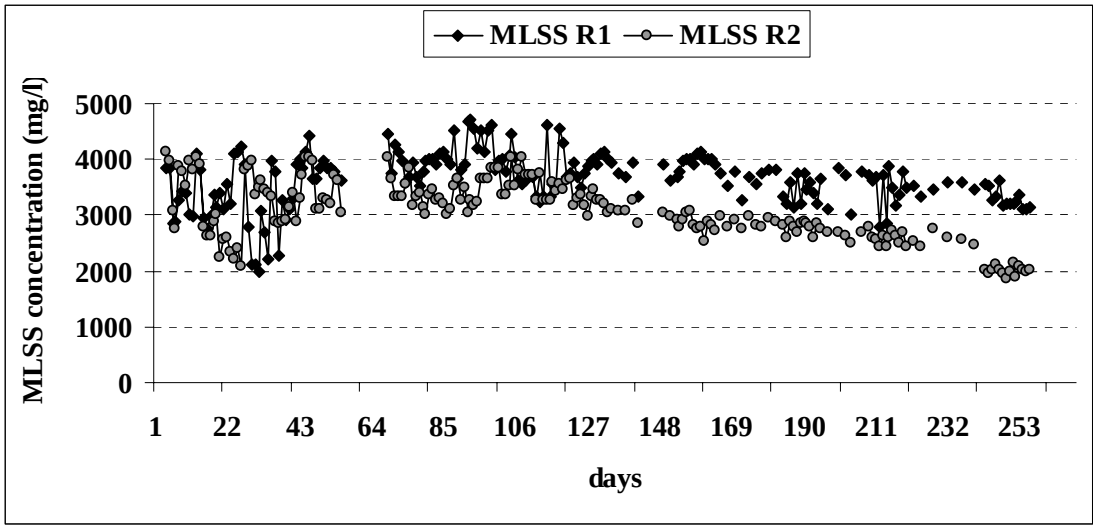


Figure 4.6.5 The biomass of both reactors R1 and R2.

Krishna and van Loosdrecht, (1999) reported that sludge settleability in systems with a low solid retention time is significantly influence by temperature, with an increased SVI being recorded at high temperature. On the other hand, the increase temperature resulted on decrease of the biomass production in system because at higher temperature, the cellular active of microorganisms were also high and required more energy to synthesize new cell. Therefore, less new cells were produced at high temperature than at low temperature (Panswad., 2001)**.**

DO concentration

These two SBR reactors were operated with anaerobic, than followed by aerobic conditions. During anaerobic condition, only mixing by propeller was applied, resulting in DO concentration averagely 0.5 mg/l. Whereas during aerobic condition, air pumps were used to supply enough air for aerobic condition, which DO concentrations were maintained around 3 mg/l.

pH values

pH values during all five phases operation of the influent, anaerobic and aerobic condition were in the ranges of 6.4-6.5, 6.8-7.0 and 8.0-8.2, respectively. The influent was mainly prepared with acetic acid, resulting in a little pH value. The uptake of VFA during anaerobic condition helped increase pH values closed to neutral. While during aerobic condition, pH values turned to a little basic range because

The summarization of all parameters such as temperature VFA, COD, TKN, NO_3 and phosphorus concentrations and phosphorus content during all five phases of R1 and R2 were described in the followings.

The first phase

The first phase was to acclimatize seed sludge with suitable condition for biological phosphorus removal. This case controlled the temperature at 20 °C of both R1 and R2 to acclimatize the raw sludge and used synthetic wastewater which had COD about 300 mg/l which enough for Bio-P bacteria. After start up Bio-P bacteria was adapted with new condition and then they could work in reactors with 20 °C.

At steady state VFA was reduced from 216 mg/l to 53 mg/l averagely in anaerobic condition of both reactors. Phosphorus released significantly during anaerobic condition. In addition, phosphorus content in biomass was also up to 11-12% in both reactors. These illustrated succeed in biological phosphorus removal in both reactors. Also, both reactors could produced effluents containing as low as 1.1 to 1.3 mgP/l of phosphorus.

As a result the operation in this the first phase indicated that the parameter in the influent at the end of anaerobic and at the end of aerobic condition as illustrated in Table 4.6.2.

Table 4.6.2 The performance at steady state of R1 and R2 in the first phase.

Parameter	Unit	Influent	R1		R2	
			Anaerobic	Aerobic	Anaerobic	Aerobic
Temperature	°c	29	20	20	20	20
VFA	mg/l	216	53	24	53	29
COD	mg/l	323	20	10	20	11
TKN	mg/l	11	2.9	1.4	3.0	1.6
NO_3	mg/l	0.06	0.2	1.3	0.2	1.3
Phosphorus	mg/l	19	67	1.1	65	1.3
Phosphorus content	%			12		11

The second phase

The second phase the R1 remain controlled temperature with 20 °C, but the R2 the temperature was increased 0.5 °C per day until to air temperature (30°C). Increasing of the temperature was about 0.5 °C per day (about three to four days) for microorganism could adapt into new temperature and to protect the shock temperature effect.

At steady state VFA was reduced from 216 mg/l to 54 mg/l averagely in anaerobic condition of reactor R1, while the average of reactor R2 was 62 mg/l. High temperature condition in R2 resulted in phosphorus release in anaerobic condition was around 49 mg/l, which less than the reactor R1. As a result, a little of phosphorus release in bulk solution of anaerobic condition was affected to small phosphorus uptake in aerobic condition and increasing of phosphorus concentration at the end of aerobic condition. In addition, phosphorus content in biomass was approximately 11% in R1 and declined to 8% in R2.

As a result, in the R2 operated with new condition indicated that the parameter in the influent at the end of anaerobic and at the end of aerobic condition as illustrated in Table 4.6.3.

Table 4.6.3 The performance at steady state of R1 and R2 in the second phase

Parameter	Unit	Influent	R1		R2	
			Anaerobic	Aerobic	Anaerobic	Aerobic
Temperature	°c	29	20	20	30	30
VFA	mg/l	215	54	27	62	30
COD	mg/l	327	20	21	21	14
TKN	mg/l	12	2.7	1.4	3.7	2.1
NO_3	mg/l	0.05	0.2	1.2	0.2	2.1
Phosphorus	mg/l	19	68	1.3	49	2.6
Phosphorus content	%			11		8.0

The third phase

The third phase, the operation was changed to like CASS operation followed CASS process the operation at Chongnonsi WWTP.

At steady state a little increases of VFA to 56 mg/l averagely in anaerobic condition of reactor R1, while R2 was increase approximately 67 mg/l which this was higher than R1. Phosphorus released slightly decrease from the second phase of both R1 and R2 during anaerobic condition, about 51 and 44 mg/l respectively. In addition, phosphorus content in biomass in reactor R1 and R2 decline to 7.9 and 5.8%, respectively. The increasing of effluent phosphorus concentration was found in both reactors. The high effluent phosphorus concentration was found in R2 approximately 2.5 mgP/l, while reactor R1 contained quite low as 1.4 mgP/l.

As a result, The operation with CASS process had VFA uptake, phosphorus release, phosphorus uptake, PHA accumulated and % P in cell decreased more than operation with SBR process slightly, which illustrated in Table 4.6.4.

Table 4.6.4 The performance at steady state of R1 and R2 in the third phase

Parameter	Unit	Influent	R1		R1	
			Anaerobic	Aerobic	Anaerobic	Aerobic
Temperature	°c	29	20	20	30	30
VFA	mg/l	210	56	24	67	32
COD	mg/l	330	23	11.2	24	17
TKN	mg/l	11.2	4.0	4.2	3.7	2.4
NO_3	mg/l	0.05	0.2	1.3	0.2	2.1
Phosphorus	mg/l	19	51	1.4	44	2.5
Phosphorus content	%			7.9		5.8

The forth phase

The forth phase, would change the influent wastewater concentration from suitable concentration for biological phosphorus removal to similar real domestic wastewater concentration used synthetic wastewater. From Table indicated that of both the R1 and R2 had the efficiency of COD, TKN, and phosphorus rapidly decreased.

At steady state the influent VFA concentration reduced to 47 mg/l averagely in anaerobic condition of both reactors. In addition, phosphorus content in biomass was also to 4.9 and 12% in reactors R1 and R2. These illustrated succeed in biological phosphorus removal in both reactors and reactor could produced was approximately 1.9 and 2 mg P/l of phosphorus.

As a result, the operation with CASS process and used synthetic domestic wastewater had VFA uptake, phosphorus release, phosphorus uptake, PHA accumulated and % P in cell decreased very fast from condition 3, which illustrated in Table 4.6.5.

Table 4.6.5 The performance at steady state of R1 and R2 in the forth phase.

Parameter	Unit	Influent	R1		R1	
			Anaerobic	Aerobic	Anaerobic	Aerobic
Temperature	°c	29	20	20	30	3
VFA	mg/l	47	31	14	35	18
COD	mg/l	85	21	12	25	16
TKN	mg/l	7.1	4.9	2.4	4.8	2.3
NO_3	mg/l	0.05	0.2	1.3	0.2	2.0
Phosphorus	mg/l	3.1	19.3	1.5	17.0	2.0
Phosphorus content	%			4.9		4.2

The fifth phase

The fifth phase that the last condition used in this study, of both R2 and R1 used real domestic wastewater that collected from Chongnonsi WWTP plant between June to July 2007. In the last phase, the average of influent COD, TKN, and phosphorus concentration were about 90 mg/l, 6.7mg/l and 2.9 mg/l, respectively, as illustrated in Table 4.6.6.

Table 4.6.6 The average COD, TKN, and phosphorus in the influent in this study

Parameter	Concentration (mg/l)
COD	90
TKN	6.7
Phosphorus	2.9

In this phase operated with CASS process and used real domestic wastewater of both R1 and R2. However, the R1 remained controlled with 20 °C on the other hand the R2 operated at air temperature. Although that, in this condition had the efficiency of COD, TKN, and phosphorus decreased, whereas the efficiency removal of this condition mostly had close to the efficiency removal in the fourth phase.

At steady state VFA was about from 24 mg/l and 27 mg/l averagely in anaerobic condition of both reactors. Phosphorus released significantly reduces during anaerobic condition in low carbon. In addition, the lowest of phosphorus content in biomass was found in this phase also up to 2-3.5% in reactors R2 and R1, respectively. Also both reactors could produce a little increase of effluents phosphorus concentration was in the range of 1.6 - 2 mg P/l.

In this phase, the efficiency of COD, TKN, and phosphorus removal of R1 and R2 as illustrated in Table 4.6.7.

Table 4.6.7 The performance at steady state of the fifth phase.

Parameter	Unit	Influent	R1		R1	
			Anaerobic	Aerobic	Anaerobic	Aerobic
Temperature	°c	29	20	20	30	30
VFA	mg/l	41	24	13	27	17
COD	mg/l	90	24	12	26	17
TKN	mg/l	6.7	4.8	2.3	6.0	3.7
NO_3	mg/l	0.05	0.2	1.3	0.2	2.1
Phosphorus	mg/l	2.9	18	1.6	14	2.0
Phosphorus content	%			3.5		2.0

4.7 The comparison results of SBR System

The performances of SBR system were obtained for a period of seven months of experimental. There were significantly differences in temperature and carbon source during the whole experiments. As a result, this experiments were divided into fives phases for investigation effects of temperature and carbon source.

4.7.1) The comparison results between the first phase and the second phase

Table 4.7.1 shows the comparison results which investigated effects of temperature on biological phosphorus removal.

Table 4.7.1 The concluded results in the first phase and the second phase of R1 and R2

Phases	Parameters						
	Temp (°C)	Influent VFA concentration (mg/l)	% P removal	% P (incell)	% PHA (in cell)	COD:P	BOD:P
Reactor R1							
1	20	216	95	12	6.3	17	12
2	20	215	94	11	5.9	17	12
Reactor R2							
1	20	216	95	11	6.1	17	12
2	20	215	87	8	4.1	17	12

Table 4.7.1 demonstrated the results in the first phase and the second phase Mostly were similarly in term of the efficiencies of phosphorus removal, phosphorus contents, and PHA contents were in the range of 94-95%, 11-12%, and 5.9-6.3%, respectively. Phosphorus contents in the range of 11-12% from this study were similar to those found in other researches, which were related to good BPR operation (Duangjai,2002). Therefore, it could be said that the good BPR performance occurred when operated at 20 °C because PAOs dominate at low temperature (Panswad et al, 2003), resulting in high efficiency of phosphorus removal. Similarly, results in the first

phase of R2, which was operated at 20 °C, also showed high efficiency of BPR. However, when the reactor R2 was operated at 20 °C in the second phase, BPR performance was lessen, e.g. phosphorus removal efficiency decrease from 95% in the first phase to 87% in the second phase. In addition, it was found that VFA consumption was reduce, which might on low PHA accumulation in biomass, resulting in low internal carbon source for phosphorus for phosphorus uptake in aerobic condition. Obviously, phosphorus content (%P in biomass) and PHA accumulation were higher in 20 °C. Therefore, it could be said that PAOs were fond of lower range mesophiles or perhaps psychrophiles environment and predominated in 20°C operation or possibly lower temperature (Pansawad; 2003). Krishna and van Loosdrecht; (1999) also reported that less PHA formation occurred at high temperature operation. Likewise, Brdjanovic et al., (1999) reported that the complete of phosphorus uptake was observed at 20°C.

As a result, it was obvious that BPR performance decreased when operating temperature increased. However, there were still not too low BPR performance in operation at 30°C, i.e. phosphorus removal efficiency was around 87% while phosphorus content was around 8%.

4.7.2 The comparison results between the second phase, the third and the forth phases

This part was to investigate the effect of the CASS operation and organic loading on biological phosphorus removal by comparison among the second phase, the third phase and the forth phase. , Results were summarized in Table 4.7.2.

Table 4.7.2 The results concluded in the second through the third phase of R1 and R2

Phases	Parameters						
	Temperature	Influent VFA concentration (mg/l)	% P removal	% P (in cell)	% PHA (in cell)	COD:P	BOD:P
Reactor R1							
2	20	215	94	11	5.9	17	12
3	20	210	93	7.9	5.4	18	13
4	20	47	63	4.9	2.1	27	14
Reactor R2							
2	30	215	87	8	4.1	17	12
3	30	210	86	5.8	3.3	18	13
4	30	47	57	4.2	1.7	27	14

As mentioned in the previous discussion, good BPR performance was found in 20°C operation, but declined as operating temperature increased to 30 °C in the reactor R2 during the second phase. Therefore, operating the configuration was changed to be similar to CASS operation during the third phase, resulting decline of BPR performance in comparison with the second phase. Efficiencies of phosphorus removal, phosphorus contents, and PHA contents of R1 in the third phase were 93%, 7.9%, and 5.4%, whereas those of R2 were 86%, 5.8%, and 3.3%, respectively. Therefore, the operating configuration of CASS slightly affected on BPR performance of both R1 and R2. The efficiencies of phosphorus removal were almost identical between the second and the third phases

In the fourth phase, influent carbon source was reduced, resulting in significant decrease of phosphorus removal efficiency from 93 to 63% in the reactor R1 (20°C), and from 86 to 57% in the reactor R2 (30°C). In addition, phosphorus content in cell decreased from 7.9 to 4.2% in R1, and from 5.8 to 4.2 in R2. PHA content appeared similarly to phosphorus content. From the results, it appeared that the change in operating configuration from general SBR to CASS-like did not affect on BPR performance evidently. But the change in COD loading significantly affected on phosphorus removal efficiencies and phosphorus and PHA contents in cell. Moreover, when consider the results from the fourth phase, operating temperatures of 20°C seemed to be similar, a little less in R2 than R1. It is thus concluded that carbon feed influence

BPR performance more than operating temperature, and CASS-like operation did not destroyed BPR performance.

4.7.3 The comparison results between the forth phase and the fifth phase

This part was to compare the effect of low carbon source using which synthetic domestic wastewater (the fourth phase) and real domestic wastewater (the fifth phase) were on BPR, results as shown in Table 4.7.3.

Table 4.7.3 The concluded results in the forth phase and the fifth phase of R1 and R2

Phases	Parameters						
	Temperature	Influent VFA concentration (mg/l)	% P removal	% P (in cell)	% PHA(in cell)	COD:P	BOD:P
Reactor R1							
4	20	47	63	4.9	3.2	27	14
5	20	41	64	3.5	2.7	31	10
Reactor R2							
4	30	47	57	4.2	2.6	27	14
5	30	41	51	2	2.1	31	10

During the fourth and the fifth phases, carbon fed was reduced and COD:P ratios were in the range of 27-31. It appears that different composition in real domestic wastewater used in the fifth phase did not affect BPR performance in comparison with the fourth phase that used synthetic wastewater. Phosphorus removal efficiencies in the operating temperature of 20 °C (R1) were almost identical between these two phases (63 and 64%). Similarly, in the 30 °C operation (R2) those efficiencies were 57 and 51% in the fourth and the fifth phases, respectively. However, there were slightly decreases in phosphorus contents and PHA contents from the fourth phase. This is possible related to the amount of soluble COD contained in real wastewater, which was less than in synthetic wastewater. It should be note that the COD:P ratio of 31 was considered from soluble COD concentration.

However, the occurrence of phosphorus release and uptake clearly appeared though carbon feds in these two phases were quite low. Referring to phosphorus removal efficiencies in Chongnonsi WWTP, those in the reactor R2 were found similarly. In spite phosphorus removal efficiency of the reactor R2 decreased to approximately 50%, low phosphorus effluent was produced.

4.8 Effect of temperature

Consideration effect of temperature on BPR, it was obvious that increase of temperature reduced BPR performance.

Figure 4.8.1-4.8.3 showed VFA uptake, P release and P uptake among all five phases in comparison between R1 and R2.

Therefore, VFA concentration was essential for effective BPR (Pitman,1999; Ruel et al., 2002) and high VFA uptake was found at low temperature (Knoop S. and Kunst S.,1998). Microorganism used VFA to produce energy and stored in form of polyhydroxyalkanoates; PHAs (WEF, ASCE and EWRI., 2006; Janssen, Meinema and van der Roest.; 2002, Henze et al., 2002). In low temperature environment, microorganism tends to store up more intracellular carbon, while require less energy for cell maintenance and activity. Therefore, higher VFA was up taken, resulting more breaks down of ATP to obtain enough energy for VFA assimilation. At low temperature operating found that phosphorus release was higher than in high temperature operating. (Ekama et al., 1983; Sell et al., 1981).

Hence, it could be stated that PAOs preferred low temperature environment than high temperature (Panswad et al., 2003), which the PAOs became more active and more competitive than warm temperature. The energy obtained from aerobic metabolism was a surplus; so the PAOs uptake more soluble phosphorus from the bulk solution and stored into their cell.

Although, the operation in high temperature was not favour to but BPR performance was still working quite well in 30°C operating. Therefore, it would appear that fair to good BPR performance was still found in 30 °C environment, which was consistent to several studies (Duangjai, 1998; Thonfkammak, 2003). When the

operation was changed to imitate CASS process operation, the results of VFA uptake, phosphorus release and uptake were not much different from the previous phase. This indicated that changing operating configuration did not significantly affect to BPR. However, it appeared that BPR performance in 20 °C operating was higher than in 30°C operating.

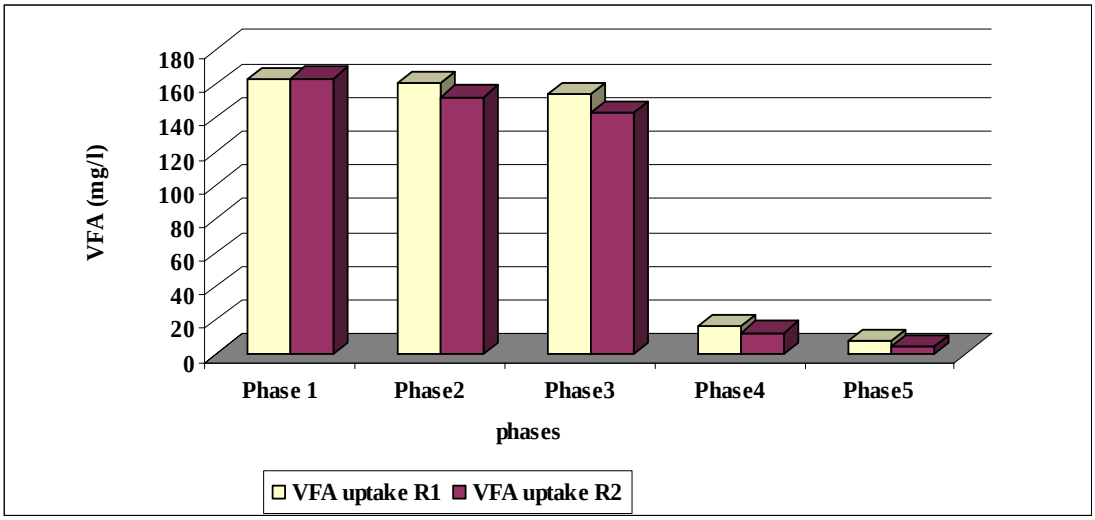


Figure 4.8.1 VFA uptake of R1 and II in five phase of this study.

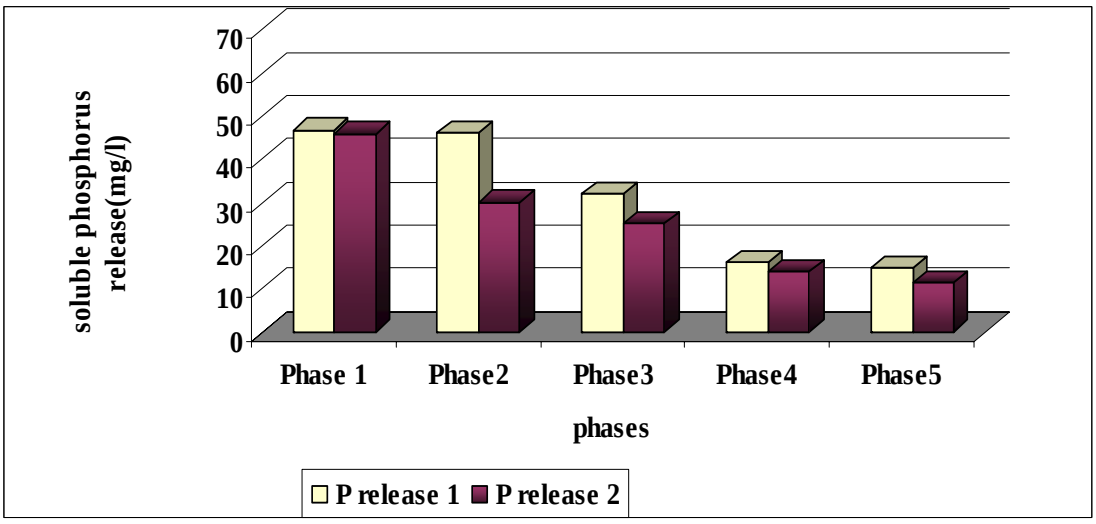


Figure 4.8.2 Soluble phosphorus release of both R1 and R2 during five phases.

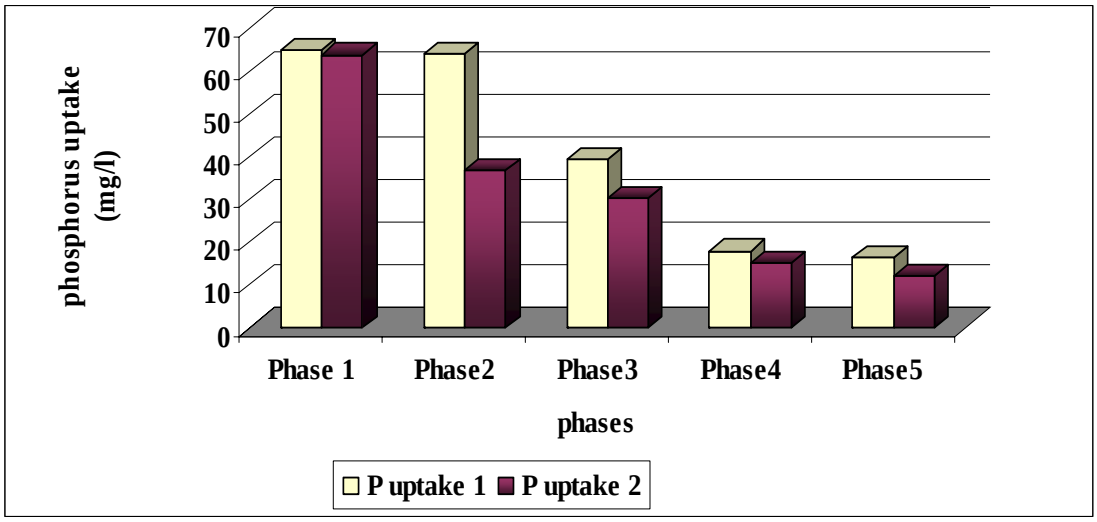


Figure 4.8.3 Soluble phosphorus uptake of both R1 and II during five phases.

4.9 Effect of carbon feed

Concerning the effect of carbon fed on BPR performance, COD:P ratios were used to determine the relationship between carbon fed and the BPR performance. COD:P ratios in all five phases were illustrated in Table 4.9.1.

Table 4.9.1 The influent COD:P and BOD:P ratios during five phases.

Phases	COD (mg/l)	Phosphorus (mg/l)	COD:P	BOD:P
1	323	20	17	12
2	327	19	17	12
3	330	19	18	12
4	85	3.1	27	13
5	90	2.9	31	10

The mass balance calculations were considered and summarized in Table 4.8.2, including phosphorus release and uptake of both reactors in each phase. The COD:TP ratio of 17 produced the greatest anaerobic phosphorus release, and aerobic uptake and the COD:TP ratio of 31 produced the least. Phosphorus uptake to phosphorus release

ratios observed during using different COD:TP ratios was calculated and tabulated in Table 4.9.2.

Table 4.9.2 COD:TP ratios of R1 and R2

Phases	COD:TP	Reactors	
		R1	R2
		P uptake/P release	P uptake/P release
1	17	1.4	1.4
2	17	1.4	1.3
3	18	1.4	1.2
4	27	1.1	1.07
5	31	1.09	1.08

Hence, the highest P uptake: P release ratios were found in the first phase of both reactors because the first phase was operated with suitable condition for BPR, consequently highest efficiency of phosphorus removal was obtained. In the third phase, both reactors R1 and R2 performed the lowest P uptake: P release ratios. appeared the lowest efficiency phosphorus removal in comparison among three phases of using the same synthetic wastewater. In the forth phase and the fifth phase COD:P ratios increased to 27 and 31, respectively, indicating that COD and phosphorus concentrations were quite low. It was possible that PAO fraction in biomass decreased, consistent to phosphorus content in biomass that decreased to only 3% and 2% in R1 and R2, respectively, in the fifth phase. Therefore, the increasing of COD:P ratio resulted in lower phosphorus content (%P) accumulated in biomass.

Mulkerrin et al., (2003) also reported about reduction in BPR performance when applied with high influent COD:P ratios.

A graph of phosphorus content in TSS versus the COD:TP ratio was illustrated in Figure 4.9.1. The phosphorus content the biomass decreased as the COD:TP ratio increased. In other words, phosphorus content in the biomass of the first the second and the third apparently higher than the forth and the fifth phases.

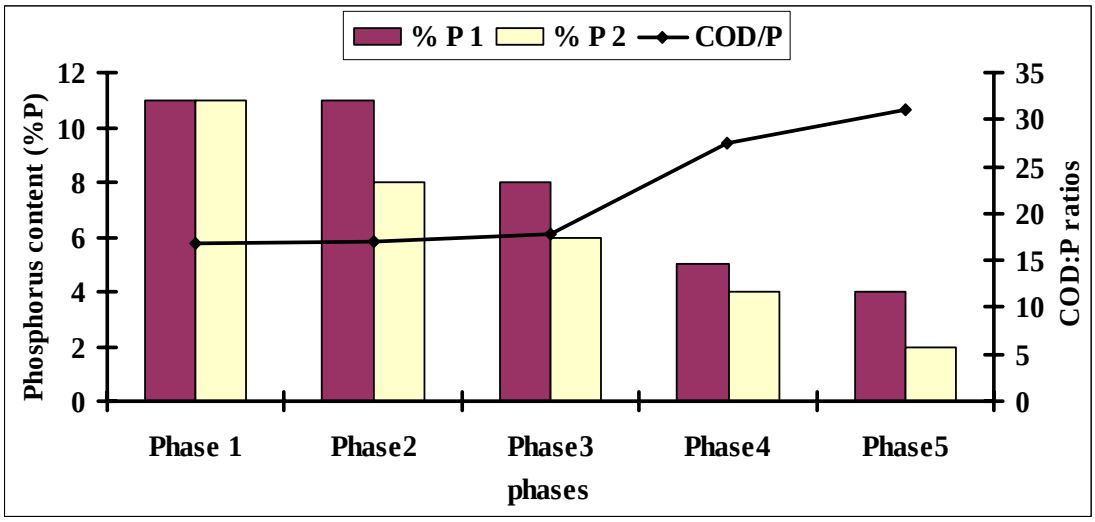


Figure 4.9.1 Phosphorus content in the biomass versus the COD:TP ratios during five phases.

As a result, effects of increases of COD:P ratio was shown in phases. the forth phase and the fifth phase. The low phosphorus removal efficiencies and phosphorus contents were found in the forth phase. Periods with low influent COD concentration fed into system, a complete cessation of the anaerobic phosphate release and to a subsequent decreased capacity for phosphate uptake (Carucci et al., 1999a). The poorest BPR performance was found in the fifth phase especially in the reactor R2, was operated with the most unsuitable condition in this part, concurrently with warm temperature of 30 °C.

Both R1 and R2 were fed with low COD, which was possible for good performance, not enough of BPR system. Thus, BPR worst quality of effluents were produced in both R1 and R2, in the forth phase and the fifth phase were limited by low amount carbon. However, the low effluent concentration was found in both R1 and R2 when operated in the forth phase and the fifth phase. Efficiencies of phosphorus removal and phosphorus contents in biomass from the reactor of R1 were approximately 60% and 3.5%, respectively. Interestingly, those obtained from the reactor R2 were approximately 50% and 2%, respectively, which were similar with to those presented in of Chongnonsi WWTP.

From the results, the influence of temperature same to be less strong than the influence of carbon fed, fair to good BPR performance could be found, while very low BPR performance appeared instantly when low carbon fed was applied.

At the end of the study could be conclude that low organic carbon was important of poor BPR performance occurrence in Chongnonsi WWTP.

The results from the experiment with SPR reactor could be used to explain the cause of poor BPR performance in Chongnonsi WWTP. This is, low carbon fed should be the main reason of low BPR in this plant.

Sub conclusion

This part of SBR reactors, which to investigate affected of temperature and low carbon feed on biological phosphorus removal. In this study of all five phase was studied.

As a result, when operated in the first phase, which it suitable condition indicated it had high phosphorus release and uptake and had high efficiency phosphorus removal was 97%. The effluent phosphorus concentration was about 1.0 mg/l. This phase the percentage of phosphorus accumulated in biomass (%P) were averaged 11 % of both R1 and R2.

Then, the operation was changed to the second phase found that the phosphorus release and uptake of the first phase was close to the second the first phase the R1. While, the R2 the phosphorus release and uptake decreased than the first phase, with percentage of phosphorus accumulated in biomass decreased to 8.3%. As a result, the efficiency of phosphorus removal decreased from 94% to 83%. Almost parameters were lower than the first phase because it operated at 30 °c. Actually, the temperature affected on biological phosphorus would indicate in the second phase.

Then, the operation changed to the third phase, which likely CASS process. Eventually, this phase was not real CASS process because it had accident design and affected to PAOs group was not work perfectly. The efficiency of phosphorus removal and the phosphorus release and uptake decreased than the second phase of both R1 and R2. The percentage of phosphorus accumulated in biomass (TSS) decreased to 7.9 %

and 5.8% in R1 and R2, respectively. The Phosphorus profile indicated that decreasing of phosphorus release in R1 had slope higher than R2. It was the affected of the operation changed.

Then, the operation changed to the forth phase and 5 that wastewater used in this studied changed to synthesis domestic wastewater and real domestic wastewater. COD and phosphorus concentrations decreased rapidly, which demonstrated that the efficiency of phosphorus removal of both R1 and R2 was decreased was in the range of 63-64% and the percentage of phosphorus accumulated in biomass (TSS) was in range 3.5-4.9% in R1. While the in R2 the efficiency of phosphorus removal and the percentage of phosphorus accumulated in biomass were in range 50-57% and 2- 4.2%, respectively.

The reasons of low the efficiency of phosphorus removal when running with domestic wastewater may be due to an insufficient of substrate (acetate) for PAOs uptake to the cell and converted to PHB (low synthesis PHB) resulting low energy from PHB degradation to glycogen synthesis, P uptake and for cell regeneration. In addition, it may be predominant with non-floc former bacteria due to low growth of PAOs. On the other hand, it can be proposed that raw domestic wastewater is low substrate in form of COD and then causes a reduction in the COD converting to the RBCOD and later the conversion to VFAs to PHB by PAOs .

As a result, the efficiency of phosphorus removal of two phases (the fourth and the fifth phases) was not different because wastewater used in these cases was a simple carbon and low COD concentration. Therefore, the decreasing of the efficiency of phosphorus removal and percentage phosphorus in cell affected from low carbon source that fed in to system and was not enough for biological phosphorus removal.

Part III

4.10 Batch Test

From the results of the first part, ineffective biological phosphorus removal (BPR) was found in CASS operation of Chongnonsi WWTP. Little VFA uptake, phosphorus release and uptake, therefore, low phosphorus removal occurred during this investigation. In addition, phosphorus contents (%P) in biomass were found in a small amount, but very slightly higher than those of bacteria in ordinary heterotrophic organism (OHO) group. However, this low biological phosphorus removal did not mean that phosphorus accumulating organisms (PAOs) were not existed in the system. Three presumptions to explain this low BPR in CASS operation of Chongnonsi WWTP could be defined, i.e. 1) there might not be any of PAOs in the system at all, 2) there were PAOs in the system, but in very low amount or 3) there were significant PAOs, but their activity was not potent.

Therefore, the experimental part was conducted as a batch test in order to investigate specific phosphorus release and uptake rates in CASS of Chongnonsi WWTP. Three sets of batch test were conducted as the followings;

(1) Determine the specific phosphorus uptake rate (SPUR) with anaerobic sludge.
(2) Determine the specific phosphorus release rate (SPRR) with aerobic sludge.
(3) Investigation with anaerobic sludge and aerobic sludge after the aeration in the second zone of CASS was reduced by turning off some air diffusers.

For the first two sets of batch test, both anaerobic and aerobic sludge were collected on March 6th, 2008, which the aeration in the second zone of CASS reactor was operated as usual. For the third set, anaerobic sludge and aerobic sludge were collected on March 13th, 2008, which the aeration in the second zone of CASS reactor was already reduced in order to increase more anaerobic condition in this zone. Triplicates were conducted for each experimental set of three batch tests.

4.10.1 Determine specific phosphorus uptake rate (SPUR) of anaerobic sludge.

Anaerobic sludge used in this batch test was taken from the area of connection between the first and the second zones (block no.1 in Figure 4.9.1), where it supposed to be the area of the most anaerobic condition. Temperature, pH values and DO concentration of taken sludge were 30 °C, 7.2 and 0.02 mg/l, respectively. After collecting, the sludge was rinsed to remove soluble organic matter with water contained some necessary ions, except carbon source. The rinse water was consisted of $NaHCO_3$ 138.4 mg/l, $MgSO_4$ 0.49 mg/l, $FeCl_3.6H_2O$ 0.5 mg/l and $CaCl_2$ 2.4 mg/l, respectively. The experimental setup in this part was shown in Appendix…. In order to determine specific phosphorus uptake rate (SPUR), this anaerobic sludge was experimented in aerobic condition as the following procedure;

- Anaerobic sludge of about 2,000 mg/l was placed in 2-litre beakers.
- Phosphorus solution was added into beaker to obtain the final concentration of 20 mg P/l.
- Enough aeration for DO supply and mixing was employed in this beaker.
- Samples were taken intermittently to determine a profile of soluble phosphorus concentrations for the duration of 120 minutes, which started at 0, 2, 5, 10, 20, 40, 60, and 90 until 120 minutes.
- Triplicates of this batch test were employed in the same time.
- Calculate SPUR from the profile of soluble phosphorus concentrations.

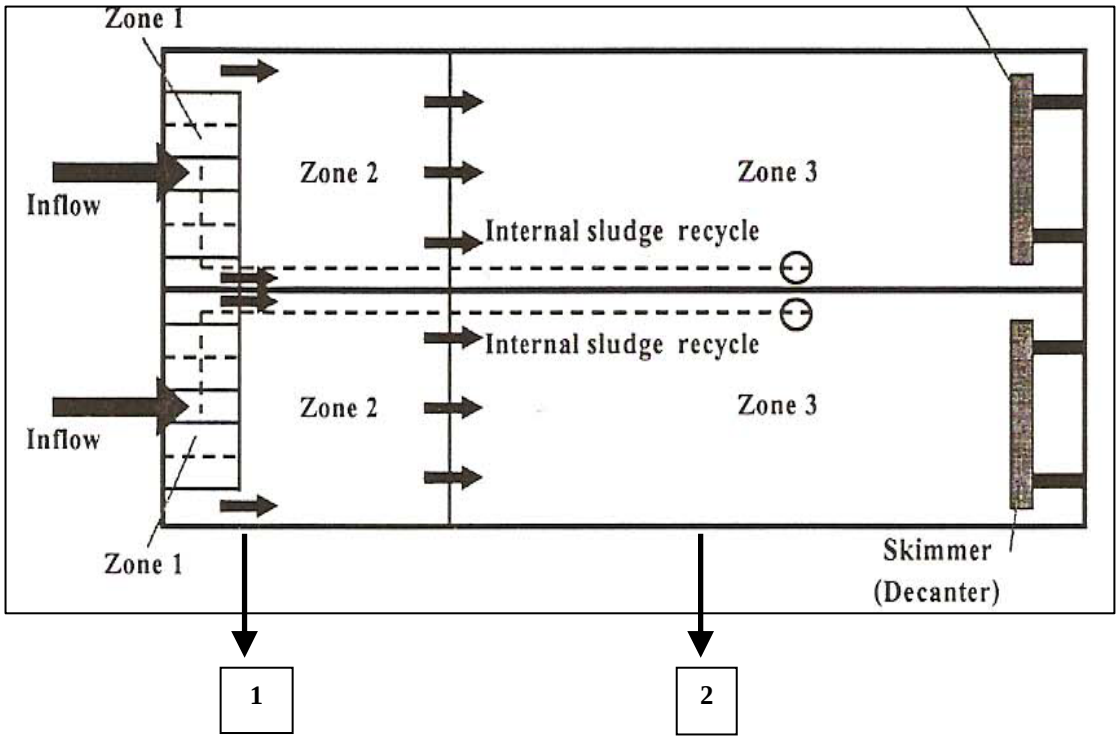


Figure 4.10.1 Sampling points for anaerobic sludge (No.1) and aerobic sludge (No.2) on March 6th, 2008.

The specific phosphorus uptake rate (SPUR)

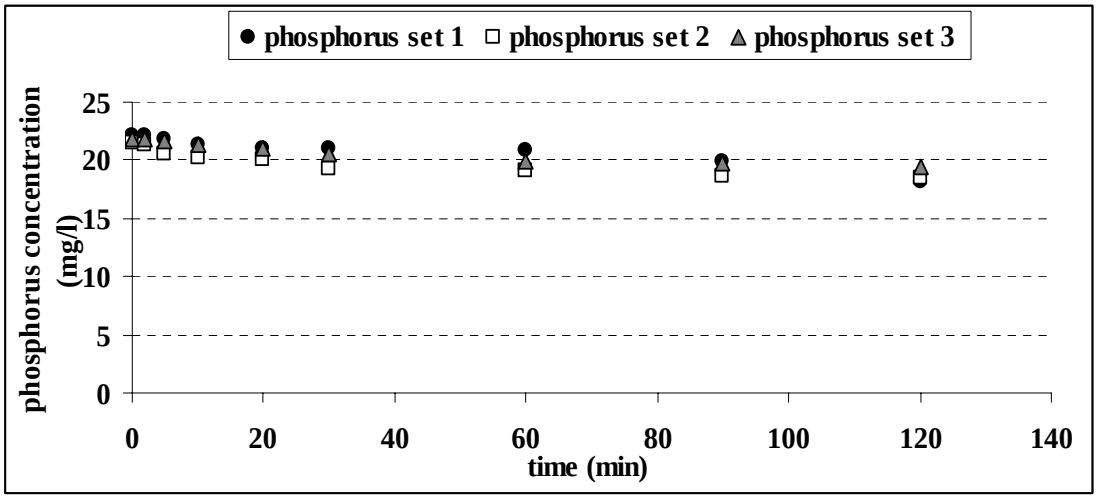


Figure 4.10.2 The soluble phosphorus all 120 minutes of anaerobic sludge

Figure 4.10.2 shows the profile of phosphorus concentration in liquid bulk according to experimental time of total 120 minutes. Phosphorus concentrations slightly decreased from the start at 22 mg P/l to the end (120 minutes) at 18 mg P/l, illustrating a little phosphorus uptaking. The average of SPUR obtained from this experimental set was 0.82 mg P/g VSS-hr, which was quite small for BPR occurrence, so the time periods must be extend for clearly result.

4.9.2 Determine specific phosphorus release rate (SPRR) of aerobic sludge.

Aerobic sludge used in this batch test was taken from the middle of the third zones (block no.2 in Figure 4.10.1) where it represented the aerobic sludge. Temperature, pH values and DO concentration of taken sludge were 30°C, 7.3 and 3.63 mg/l, respectively. After collecting, the sludge was rinsed to remove residual organic matter and phosphorus from the mixed liquor with the same rinse water used with anaerobic sludge. The experimental setup in this part was shown in Appendix J in order to determine specific phosphorus release rate (SPRR), this aerobic sludge was experimented in anaerobic condition as the following procedure;

- Aerobic sludge of about 2,000 mg/l was placed in 2-litre beakers with enough mixing to suspend sludge.
- Acetic acid was fed as a carbon source with the final concentration of 300 mg/l.
- A cover was provided to reduce oxygen diffused from air to liquid bulk as much as possible.
- DO monitoring was also applied to ensure the mixing was enough, but not supply too much DO to mixed liquor.
- Samples were taken intermittently to determine a profile of soluble phosphorus concentrations for the duration of 120 minutes, which started at 0, 2, 5, 10, 20, 40, 60, and 90 until 120 minutes.
- Triplicates of this batch test were employed in the same time.
- Calculate SPRR from the profile of soluble phosphorus concentrations.

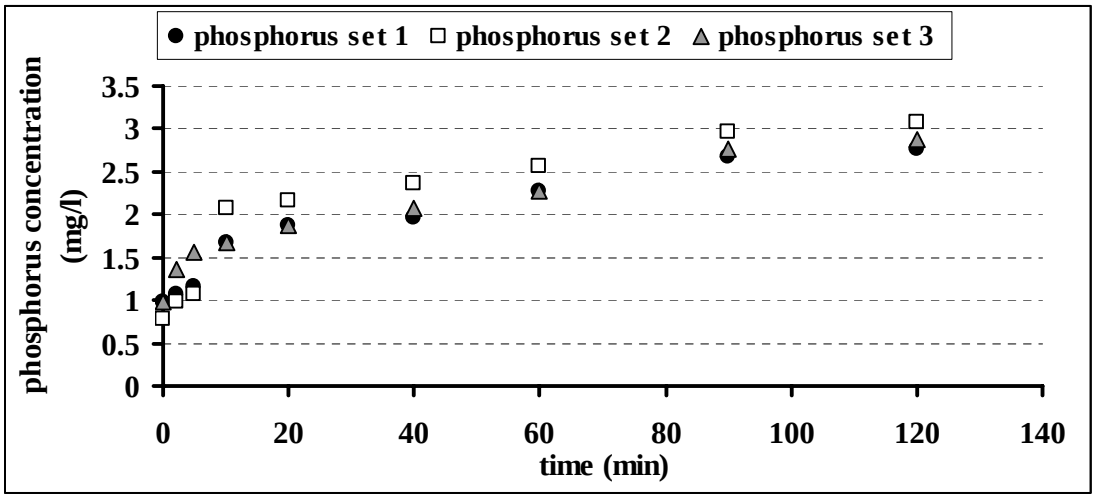


Figure 4.10.3 The soluble phosphorus of all 120 minutes of aerobic sludge

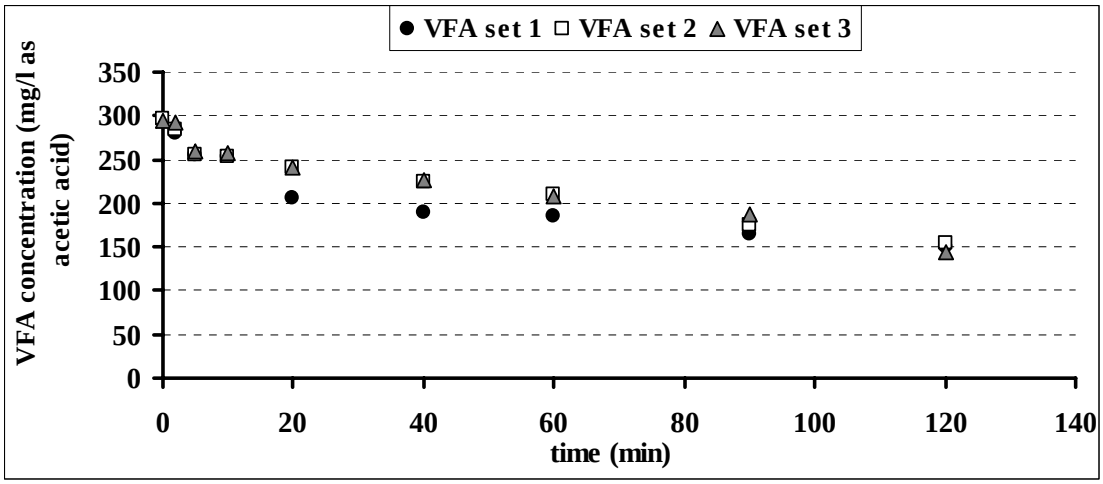


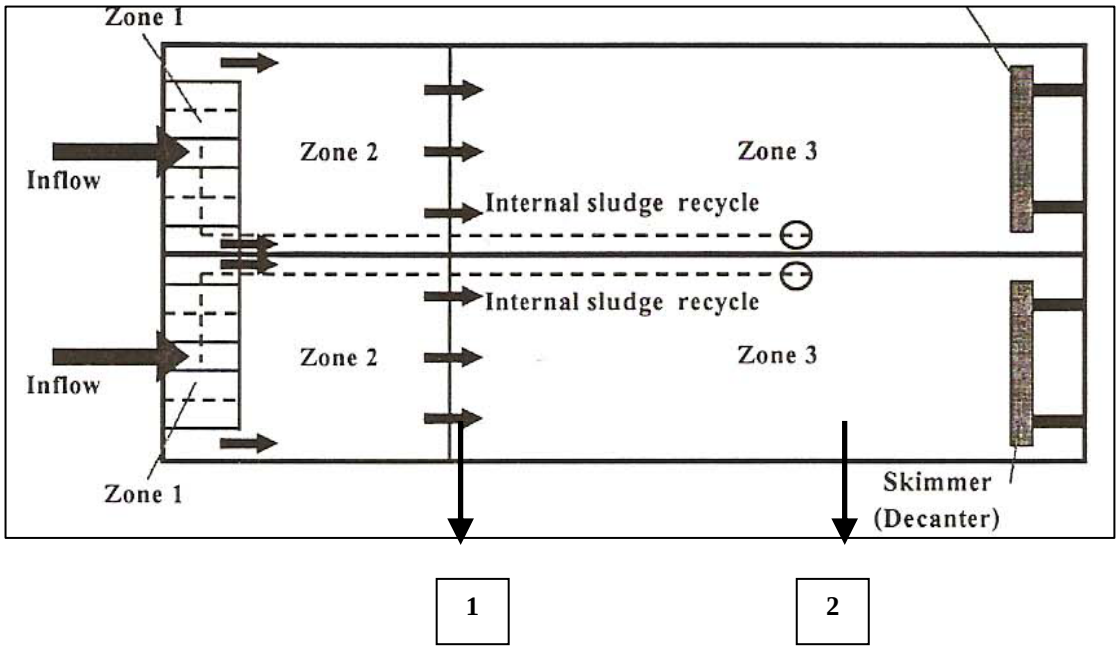
Figure 4.10.4 The VFA concentration of all 120 minutes of aerobic sludge

Figures 4.10.3 and 4.10.4 show the profiles of soluble phosphorus and VFA concentrations of this experiment, respectively. The average of SPRR of aerobic sludge was 0.82 mgP/g VSS-hr which was quite less for BPR plant. These figures illustrated that phosphorus release was more rapid during the first 10 minutes, which was concurrent with rapid VFA decrease during the same minutes. After 10 minutes, phosphorus release and VFA uptake were still occurred, but apparently with slower rates.

The low SPUR of 0.82 and SPRR of 0.78 mg P/g VSS–hr evidently illustrated weak biological phosphorus removal in the sludge taken from Chongnonsi WWTP. Therefore, the observations indicated that there was quite low of BPR potency in sludge taken from CASS reactors of Chongnonsi WWTP, which might be explained that there was very low fraction of polyphosphate accumulating organisms (PAOs) in the seed sludge or PAOs could not act with their full ability.

4.10.3 Investigation with anaerobic sludge and aerobic sludge after the aeration in the second zone of CASS was reduced by turning off some air diffusers

From the previous batch tests, the only conclusion could be drawn from those results is there was very low BPR activity in those sludge (or CASS reactors of Chongnonsi WWTP). The cause(s) of such low BPR activity is still not clear; it might be due to the amount of PAOs was low (or none), or PAOs was not invigorated enough to exhibit BPR activity. Therefore, this experimental set was set up with a little different procedure from the previous sets, which will be further described in the following details. In addition, there was some modification in CASS operation of Chongnonsi WWTP a few days before the sludge was taken (on March 13th, 2008), that is, the aeration in the second zone was reduced by turning off some air diffusers in this zone. This action resulted in settling of mixed liquor in the second zone of CASS reactor and difficulty in sludge taking. Hence, anaerobic sludge taking point was moved to the area of connection between the second and the third zones as shown in Figure 4.10.5. The average DO concentration in this area was around 0.03 mg/l, which was still represented anaerobic condition. For aerobic sludge, it was still taken from the same area as done in the previous batch tests.



Block 1 was sampling area for anaerobic sludge
Block 2 was sampling area for aerobic sludge

Figure 4.10.5 Sampling station for anaerobic sludge and aerobic sludge after the aeration in the second zone of CASS was reduced by turning off some air diffusers

The experimental set using anaerobic sludge

With the assumption that, the PAOs might be not invigorated enough because of low COD/P ratio in wastewater fed into Chongnonsi WWTP, this anaerobic sludge was further experimented in anaerobic condition without need for rinsing (as carbon source was necessary). The reason was to stimulate good anaerobic sludge with proper carbon source (VFA i.e. acetic acid) for BPR activity. Specific phosphorus release rate (SPRR) was determined during this period. Then, this sludge was further exposed to aerobic condition to evaluate specific phosphorus uptake rate (SPUR), phosphorus was added at the initial of this period. Consequently, this sludge was further exposed to anaerobic condition again; acetic acid was added and the second SPRR was determined in order to compare with the first one.

From the previous batch test, it was found that only VFA of 150 mg/l was used within 120 minutes (from feed of 300 mg/l), therefore, acetic acid added in this experimental set was reduced to around 150 mg/l in expectation of the least residual VFA (carbon source) at the end of anaerobic period. Also, each period (anaerobic or aerobic) was observed only 90 minutes, which was enough for SPRR and SPUR observation and calculation. The procedure in detail of this experimental set was described as the followings;

- Anaerobic sludge of about 2,000 mg/l was placed in 2-litre beakers with enough mixing to suspend sludge.
- Acetic acid was fed as a carbon source with the final VFA concentration of 150 mg/l.
- A cover was provided to reduce oxygen diffused from air to liquid bulk as much as possible.
- DO monitoring was also applied to ensure the mixing was enough, but not supply too much DO to mixed liquor.
- Samples were taken intermittently to determine a profile of soluble phosphorus and VFA concentrations for the duration of 90 minutes, which started at 0, 2, 5, 10, 20, 40 and 60, until 90 minutes.
- Calculate SPRR from the profile of soluble phosphorus concentrations.
- Then, start the aerobic condition by providing aeration into this beaker and add phosphorus solution for the final concentration of 20 mg P/l.
- Samples were taken intermittently to determine a profile of soluble phosphorus concentrations for the duration of 90 minutes, which started at 0, 2, 5, 10, 20, 40, 60, and 90 minutes.
- Calculate SPUR from the profile of soluble phosphorus concentrations.
- Then, the second anaerobic condition was applied with addition of another 150 mg/l of VFA. Repeat the steps of the first anaerobic condition.
- Samples were taken intermittently to determine a profile of soluble phosphorus and VFA concentrations for the duration of 90 minutes, which started at 0, 2, 5, 10, 20, 40 and 60, until 90 minutes.
- Calculate the second SPRR from the profile of soluble phosphorus concentrations.

The experimental set using aerobic sludge

In this set, aerobic sludge was taken in the same area as the previous sets, but was not rinsed with rinse water. Temperature, pH values, and DO concentration of taken sludge were 30°C, 7.4 and 3.72 mg/l, respectively. This sludge was also experimented in anaerobic condition to determine SPRR, then, exposed to aerobic condition to determine SPUR. Like the experimental set using anaerobic sludge, aerobic sludge was also not rinsed with rinse water, and the same concentrations of acetic acid and phosphorus was added in this experimental set. The procedure in detail of this experimental set was described as the followings;

- An aerobic sludge of about 2,000 mg/l was placed in 2-litre beakers with enough mixing to suspend sludge.
- Acetic acid was fed as a carbon source with the final concentration of 150 mg/l.
- A cover was provided to reduce oxygen diffused from air to liquid bulk as much as possible.
- DO monitoring was also applied to ensure the mixing was enough, but not supply too much DO to mixed liquor.
- Samples were taken intermittently to determine a profile of soluble phosphorus concentrations for the duration of 90 minutes, which started at 0, 2, 5, 10, 20, 40, 60, and 90 minutes.
- Calculate SPRR from the profile of soluble phosphorus concentrations.
- Then, start the aerobic condition by providing aeration into this beaker and add phosphorus solution for the final concentration of 20 mg P/l.
- Samples were taken intermittently to determine a profile of soluble phosphorus concentrations for the duration of 90 minutes, which started at 0, 2, 5, 10, 20, 40, 60, and 90 minutes.
- Calculate SPUR from the profile of soluble phosphorus concentrations.

The details of batch experiments were using both anaerobic and aerobic sludge taken from Chongnonsi WWTP **on March 13th, 2008** was summarized in Table 4.10.1.

Table 4.10.1. The details of batch experiment using sludge taken on March 13th, 2008.

Sludge	Condition/Determination	Condition/Determination	Condition/Determination
Anaerobic sludge	• Anaerobic condition • 1st SPRR analysis • Add VFA= 150 mg/l	• Aerobic condition • SPUR analysis • Add P = 20 mg/l	• Anaerobic condition • 2nd SPRR analysis • Add VFA= 150 mg/l
Aerobic sludge	• Anaerobic condition • SPRR analysis • Add VFA= 150 mg/l	• Aerobic condition • SPUR analysis • Add P = 20 mg/l	

The results of batch tests using both anaerobic and aerobic sludges taken from Chongnonsi WWTP on March 13th, 2008 will be discussed together as the followings.

Anaerobic sludge

Figure 4.10.6 shows the profile of phosphorus concentration during the first 90 minutes (to determine the 1st SPRR). Due to this sludge was used in the experiment without rinse, the initial phosphorus concentration was around 3.2 mg P/l, then increased to almost 4 mg P/l within 10 minutes. This illustrated there was phosphorus releasing in anaerobic condition, concurrent with rapid decrease of VFA during the same 10 minutes (Figure 410.7). Calculation of SPRR from this graph resulted in the 1st SPRR of 1.5 mg P/g VSS-hr.

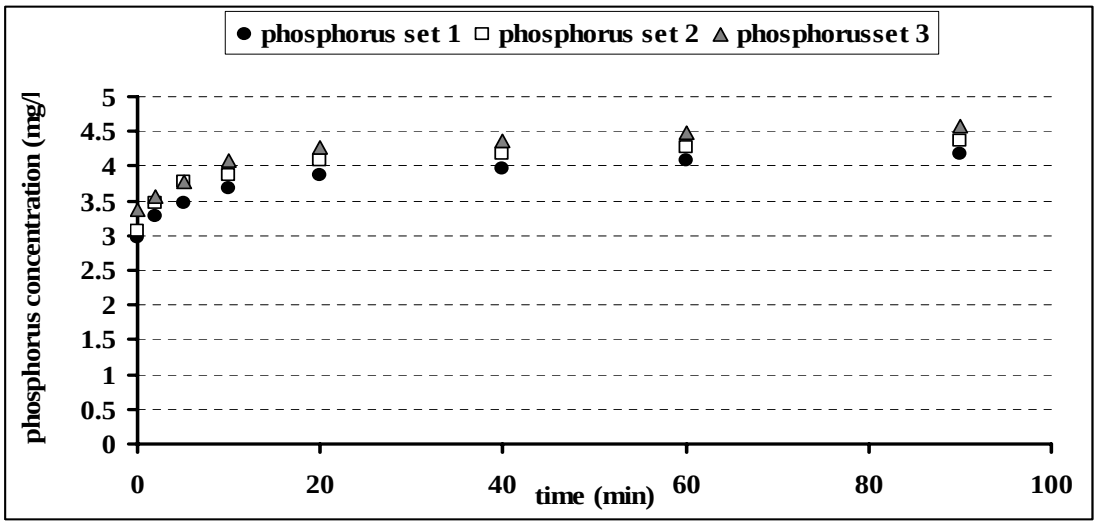


Figure 4.10.6 Profile of phosphorus concentration of anaerobic sludge for the 1st SPRR determination.

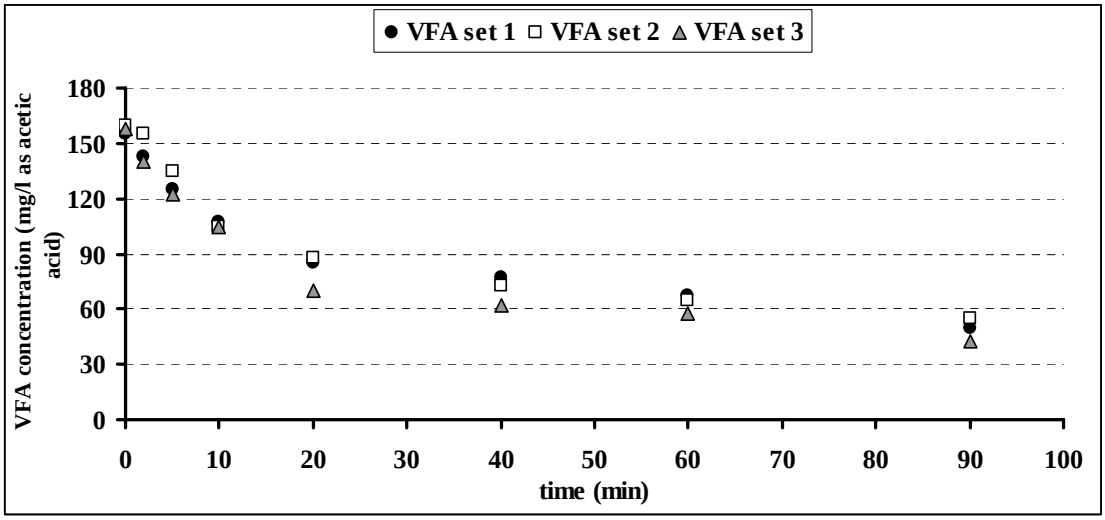


Figure 4.10.7 Profile of VFA concentration of anaerobic sludge for the 1st SPRR determination.

After 90 minutes passed, the operation was changed to aerobic condition for another 90 minutes in order to investigate phosphorus uptake. Phosphorus was added with the final concentration of around 23 mg P/l as shown in Figure 4.10.8. Phosphorus concentration decreased to around 19 mg P/l within 10 minutes, illustrating some phosphorus uptake. The SPUR of 4.1 mg P/g VSS-hr was obtained from this graph.

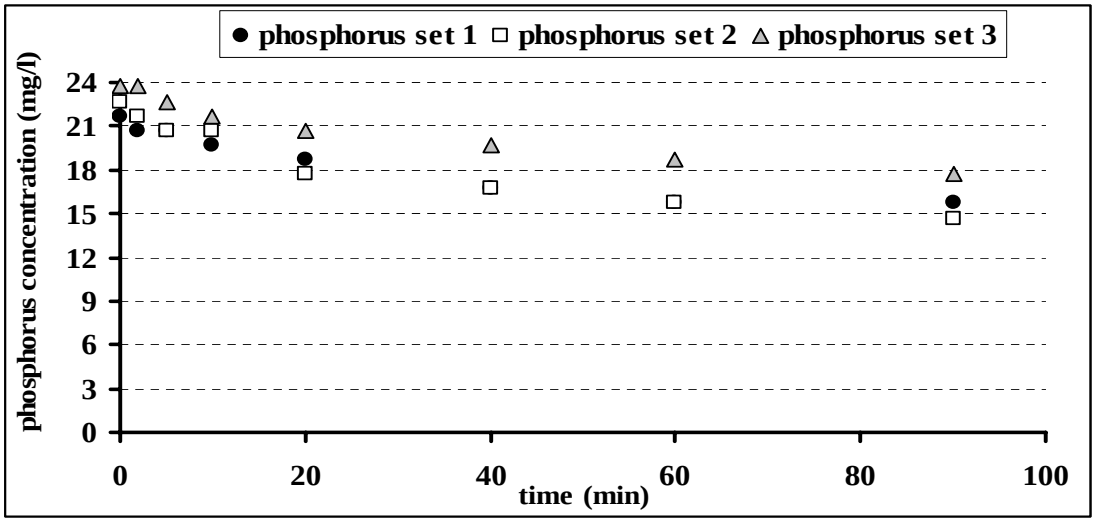


Figure 4.10.8 Profile of phosphorus concentration of anaerobic sludge for SPUR determination.

Furthermore, after 90 minutes of aerobic condition, the operation was changed back to anaerobic condition again and acetic acid of 150 mg/l was added. This second anaerobic condition was conducted in order to investigate SPRR of this sludge after exposed with abundant VFA and phosphorus for P release and uptake in the previous 120 minutes, respectively. Figure 4.10.9 shows the profile of phosphorus concentration during the last 90 minutes. Rapid phosphorus release and VFA decrease (Figure 4.10.10) occurred during the first 10 minutes similar to those in the first 90 minutes. SPRR of 4.0 mg P/g VSS-hr was obtained from this graph, which increase than the first SPRR of 1.5 mg P/g VSS-hr. Also, VFA uptake rates from both anaerobic conditions were almost identical. Therefore, this result could indicate that the amount of PAOs in this sludge were not much enough to perform good BPR though they were stimulated with proper condition and substrate.

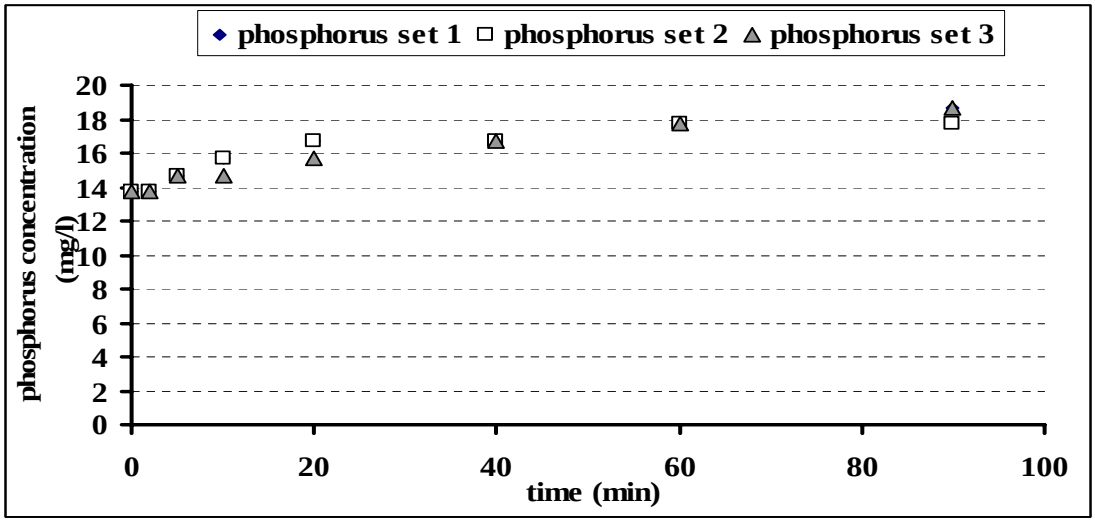


Figure 4.10.9 Profile of phosphorus concentration of anaerobic sludge for the 2nd SPRR determination.

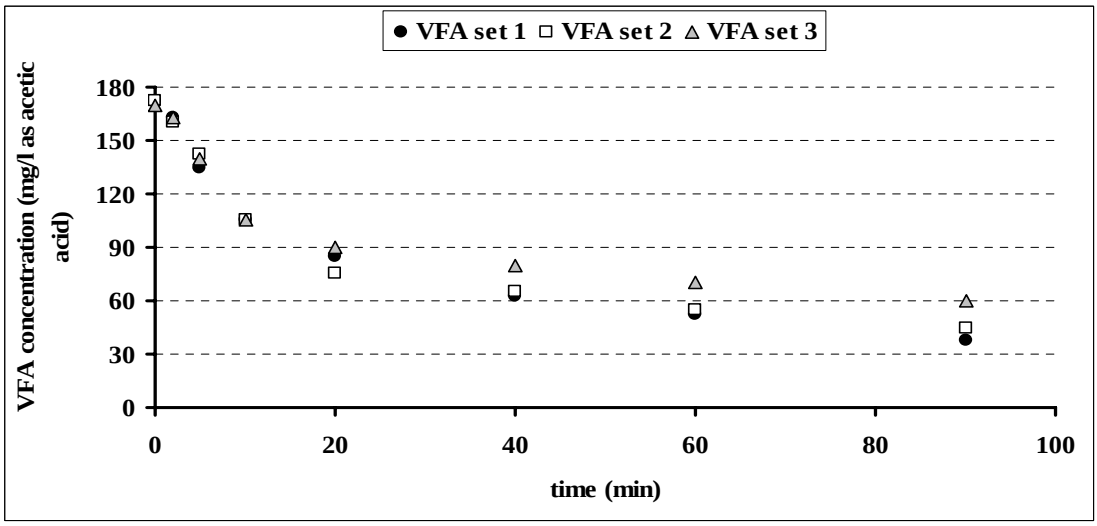


Figure 4.10.10 Profile of VFA concentration of anaerobic sludge for the 2nd SPRR determination

Aerobic sludge

Figure 4.10.11 shows the profile of phosphorus concentration during the first 90 minutes (to determine SPRR). Similar to anaerobic sludge, this sludge was used in the experiment without rinse. However, the initial phosphorus concentration was around 2.1 mg P/l, which less than that in anaerobic sludge because this aerobic sludge was taken from the fully aerobic zone of CASS reactor. Then, there was rapid phosphorus release during the 10 minutes, resulting increase of phosphorus concentration to around 2.8 mg P/l. VFA concentration as shown in Figure 4.10.12 was reduced with similar rate to that of anaerobic sludge. SPRR of 1.2 mg P/g VSS-hr was calculated from Figure 4.10.11, which is also quite closed to the 1st SPRR of anaerobic sludge (1.5 mg P/g VSS-hr. This could indicate that the stimulation of anaerobic sludge with abundant VFA was not able to significantly enhance phosphorus release.

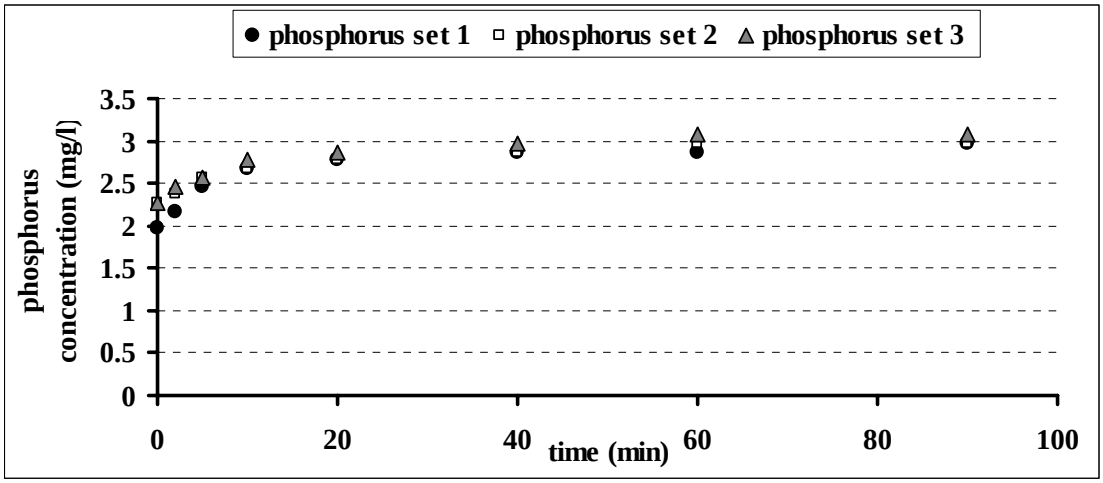


Figure 4.9.11 Profile of phosphorus concentration of aerobic sludge for SPRR determination.

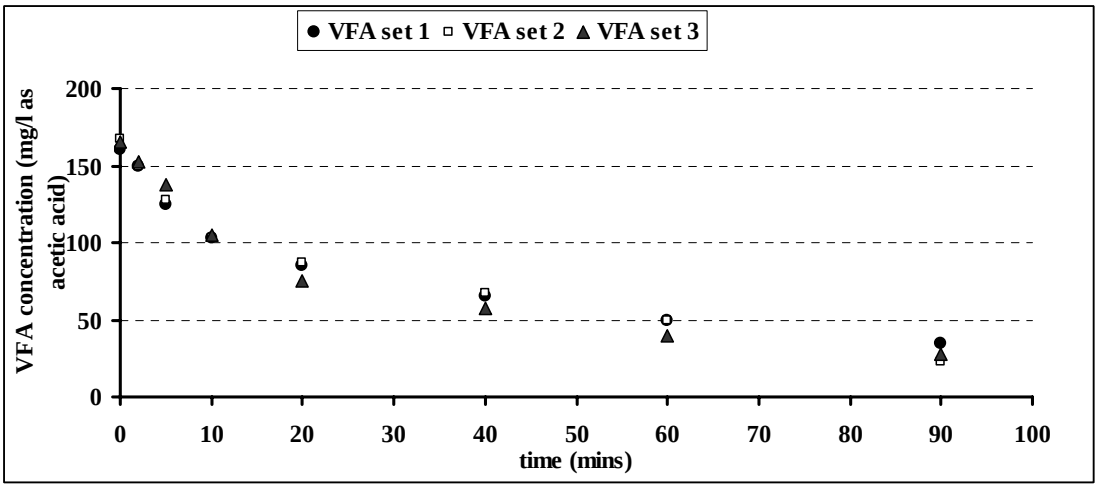


Figure 4.10.12 Profile of VFA concentration of aerobic sludge for SPRR determination

After 90 minutes, the operation was changed to aerobic condition for another 90 minutes in order to investigate phosphorus uptake. Phosphorus was added with the final concentration of around 22 mg P/l as shown in Figure 4.10.13. Phosphorus concentration decreased to around 19 mg P/l within 10 minutes, illustrating some phosphorus uptake. SPUR of 4.4 mg P/g VSS-hr was obtained from this graph, which is quite different from SPUR of 4.1 mg P/g VSS-hr obtained from anaerobic sludge. This could be resulted from stimulate anaerobic sludge with abundant VFA substrate. It is possible that this action with anaerobic sludge did enhance phosphorus uptake although did not significantly enhance phosphorus release in comparison with aerobic sludge.

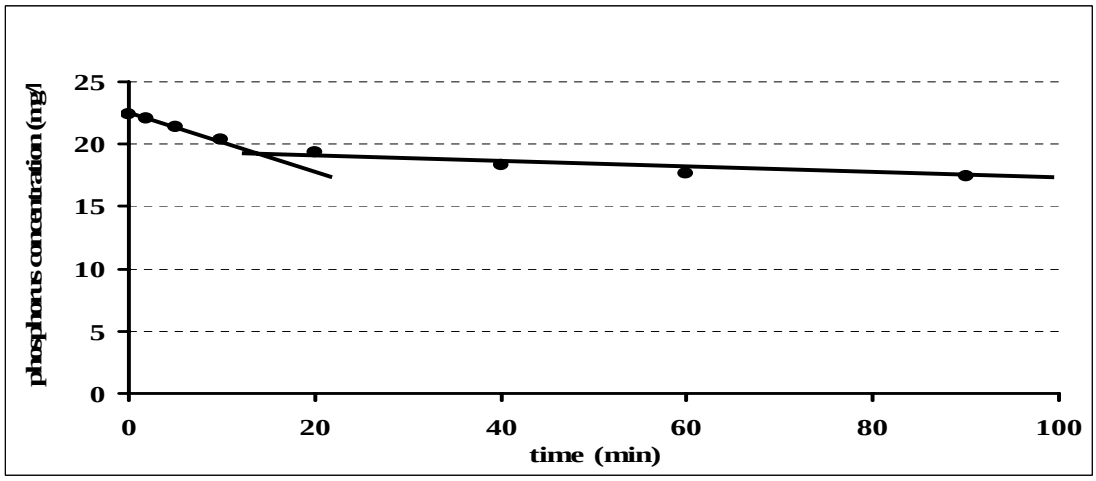


Figure 4.10.13 Profile of phosphorus concentration of aerobic sludge for SPUR determination.

Therefore, of all batch test sets finished could be said that Chongnonsi WWTP is a little BPR because the phosphorus release and uptake was occurrenced. The SPRR and SPUR was quite less than some BPR plants, as illustrated in Table 4.10.2.

Table 4.10.2 The SPRR and SPUR of aerobic and anaerobic sludge, before and after Some aeration in the second zone was turned off.

Sludge	Condition 1	Condition 2	Condition 3
Aerobic sludge Soluble Phosphorus =1.7 mg/l	**Before some aeration in the second zone was closed**	To determine SPRR Addition with VFA= 300 mg/l SPRR=0.82	
Aerobic sludge Soluble Phosphorus = 2.2 mg/l		To determine SPUR Addition with P= 20 mg/l SPRR= 0.78	
	After some areation in the scond zone was closed		
Aerobic sludge COD = 27 mg/l VFA = 19 mg/l Soluble Phosphorus = 1.17 mg/l	**To determine/Addition with** SPRR* VFA= 150 mg/l SPRR = 1.20	SPUR* P = 20 mg/l SPUR = 4.4	
Anaerobic sludge COD = 63 mg/l VFA = 54 mg/l Soluble Phosphorus = 2.25 mg/l	**To determine** SPRR* VFA= 150 mg/l 1^{st} SPRR = 1.5	SPUR* P = 20 mg/l SPUR = 4.1	SPRR* VFA= 150 mg/l 2^{nd}SPRR = 4.0

Remark; * The unit of SPRR and SPUR were mgP/gVSS-h

Discussion of batch tests

The SPRR and SPUR when the aerations in the second zone of CASS basin sill turned on was about 0.78 and 0.82 mgP/gvss-hr, respectively.

This section studied when the first and the second set of batch test finished. The SPRR and SPUR of aerobic sludge were average 1.2 and 4.4 mg/l. 1stSPRR, SPUR and 2ndSPRR2 of anaerobic sludge were average 1.5, 4.1 and 4.0 mg/l, respectively. When compared the SPRR and SPUR with the first and the second set indicated that the third set was values higher than the first and the second set. Therefore, it would be able to occurred anaerobic zone better than section 1, as illustrated Table.

As a result, after aeration in the second zone was turned off the SPRR and SPUR increased. It affected to the second zone was real anaerobic and increased VFA production. Therefore, it was consistent with the expected outcome, which some aeration was turned off and affected to increase the SPRR and VFA uptake rate. Other WWTP had the different SPUR that almost WWTP had higher SPUR than Chongnonsi WWTP, as illustrated in Appendix G.

The appendix G demonstrated that the aerobic phosphorus uptake of all twelve WWTP. Amersfoot and Haaelem-Woorderpolder WWTPs had the aerobic phosphorus uptake were about 1.2 and 2.0 mg/gVSSs.h, which moderate for EBPR process. Maastricht-Bosscherveld, Katwould, Goor, Putte,Oud-Beijerland, Venlo, Waorde, and Zettem WWTPs, which the aerobic phosphorus uptake were in the range of 3-7 mg/gVSSs.h. These indicated that it was in the range good for EBPR process. Therefore, Hardenberg and Elburg WWTPs was higher aerobic phosphorus uptake were about 12.1 and 8 mg/gVSSs.h, which very good for EBPR (Janssen, Meinema and Roest., 2005).

The phosphorus uptake rate of Chongnnsi WWTP before some aeration was turned off was about 0.82 mg/gVSSs.h, which was quite less for EBPR system as compared with other BPR plants. Then some aeration in the second zone was turn off demonstrated that the phosphorus uptake rate increased to 4.1 mg/gVSSs.h because the suitable condition in the second zone occurrence. Even though, the increasing of the phosphorus uptake rate to 4.1 mg/gVSSs.h, which more than 3.0 mg/gVSSs.h that the minimum of the recommendation (Janssen, Meinema and Roest., 2002).

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The aim of this study was to investigate high temperature and low carbon feed on biological phosphorus removal.

Phosphorus removal efficiency in Chongnonsi WWTP was up to 50%, which phosphorus was assimilated for cell synthesis more than significantly preceded biological phosphorus removal. Consequently, batch tests were setup to determine the SPRR and SPUR of biomass in CASS reactors of Chongnonsi WWTP. The results presumably identified small fraction of PAOs in biomass, therefore, weak BPR performance occurred in Chongnonsi WWTP. From batch test results, the capability of PAOs in Chongnonsi WWTP is promising for good BPR.

Results from all five phases of SBR experiment illustrated the declination of BPR performance and phosphorus content in biomass when temperature increased from 20 °C to 30 °C. However, there was moderate to high potential of BPR even operating at high temperature such as 30°C. When the operating configuration was changed to imitate CASS process operation of Chongnonsi WWTP, the changed configuration did not significantly affected on BPR performance. Changing the carbon fed from COD:TP ratios of 17:1 during the first through the third phases to approximately 27:1 and 31:1 during the fourth phase and the fifth phase, respectively, did not greater effect on BPR performance than temperature did. Those resulted in poor BPR performance with phosphorus removal efficiency declined to 50%, which was similar to the general of Chongnonsi WWTP.

In conclusion, the problem of weak BPR performance in Chongnnonsi WWTP was possibly caused by low organic carbon and phosphorus concentrations (high COD:TP ratio) more than effect of high temperature. Therefore, additional carbon and phosphorus source for feeding into CASS reactors would be recommended.

5.2 Recommendations

This study indicated that low carbon feed played more important role in affecting on biological phosphorus removal. Therefore, primary sludge of this Chongnonsi WWTP should be considered to be an additional source of carbon and phosphorus for feeding into CASS reactors.

Other recommendations for further investigation should be as the following;

- Investigation the potential of VFA formation from primary sludge.
- Investigation the relationship between PAOs and GAOs during operation at temperatures of 20 °C and 30°C.
- Investigation the characteristics of PHAs and glycogen formation in biomass.

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APPENDIX

APPENDIX A

The calculation of prepare the synthesis wastewater

1) COD

The COD concentration used in this study was about 300 mg/l. Therefore, this COD concentration could divide from nutrient broth about 80 mg/l and from acetic acid about 220 mg/l.

- Nutrient broth 1.0 gram has COD concentration about 1,000 mg.

  COD used in this study 80 mg.

  Used nutrient broth 0.08 g/synthesis wastewater 1 liter.

- COD concentration from acetic acid that prepare from this equation

$$CH_3COOH + 2O_2 \longrightarrow H_2O + 2CO_2$$

The MW of CH_3COOH was about 60

The MW of O_2 was about 32

Used acetic acid = 220*60/ (2*32) mg.

= 206 mg.

The acetic acid used in this study 1 ml. has acetic acid 1.049 g. and has purity 99.9%. Therefore the acetic acid concentration was about 1048 mg/ml.

Used acetic acid = 206/1048 mg.

= 0.2 ml/synthesis wastewater 1 liter.

2) Nitrogen

The total nitrogen concentrations used in this study receive from only nutrient broth. Therefore, of all experiments the external nitrogen was not added in the synthesis wastewater. As a result, the nitrogen concentrations from nutrient broth were about 11.0 mg/l (from the experiments).

3) Phosphorus

The total phosphorus concentrations were about 20 mg/l, which prepare from KH_2PO_4 98%

The MW of KH_2PO_4 was about	=	136	
Used KH_2PO_4	=	20*(136/31)*(1/0.98)	
	=	89.6	mg.

4) The alkalinity

The alkalinity 400 mg/l as $NaHCO_3$ which prepare from $NaHCO_3$ 99.5%. (the alkalinity 300 mg/l as $NaHCO_3$) and from tap water (the alkalinity 100 mg/l as $NaHCO_3$)

The MW of $NaHCO_3$ was about	=	84	
the alkalinity 300 mg/l., used $NaHCO_3$	=	(84*300)/(61*0.995)	
	=	415	mg.

5) Magnesium

The magnesium 2.88mg/l., prepare from solution of $MgSO_4.7H_2O$ that have the concentration about 80g/l. (P:Mg ratio was about 1: 0.25 mole)

The phosphorus used in this study	=	0.015/31	mole
	=	$0.48x10^{-3}$	mole
The magnesium used in this study	=	$0.25x0.48x10^{-3}$	mole
	=	2.88	mg

The MW. of $MgSO_4.7H_20$	=	246	
$MgSO_4.7H_20$ (l) 1 liter has Mg	=	80*(24/246)	
	=	7.8	g.
The $MgSO_4.7H_20$ used in this study	=	2.88/7.8	
	=	0.36	ml.

6) Iron

The iron 1.5 mg/l., prepare from solution of $FeCl_3.6H_2O$ that have the concentration about 15 g/l. (COD:Fe ratio was about 100: 0.5 mole)

The COD used in this study	=	300	mg/l
The iron used in this study	=	1.5	mg/l
The MW. of $FeCl_3.6H_2O$	=	270.5	
$FeCl_3.6H_2O$ (l) 1 liter has Fe	=	15*(56/270.5)	
	=	3.1	g.
The $FeCl_3.6H_2O$ (l) in this study	=	1.5/3.1	
	=	0.48	ml.

7) Calcium

The calcium 9.6 mg/l., prepare from solution of $CaCl_2$ that have the concentration about 50 g/l. (P:Ca ratio was about 1: 0.5 mole)

The phosphorus used in this study	=	0.015/31	mole
	=	$0.48x10^{-3}$	mole
The calcium used in this study	=	$0.5x0.48x10^{-3}$	mole
	=	9.6	mg
The MW. of $CaCl_2$	=	110	
$CaCl_2$ (l) 1 liter has Ca	=	50*(40/110)	
	=	18.2	g.
The $CaCl_2$ (l) in this study	=	9.6/18.2	
	=	0.353	ml.

APPENDIX B

The calculation of prepare the synthesis domestic wastewater

1)COD

The COD concentration used in this study was about 100 mg/l. Therefore, this COD concentration could divide from nutrient broth about 30 mg/l and from acetic acid about 70 mg/l.

a. Nutrient broth 1.0 gram has COD concentration about 1,000 mg.

COD used in this study 30 mg.

Used nutrient broth 0.03 g/synthesis wastewater 1 liter

- COD concentration from acetic acid that prepare from this equation

$$CH_3COOH + 2O_2 \longrightarrow H_2O + 2CO_2$$

The MW of CH_3COOH was about 60

The MW of O_2 was about 32

Used acetic acid = 70*60/ (2*32) mg.

= 65.63 mg.

The acetic acid used in this study 1 ml. has acetic acid 1.049 g. and has purity 99.9%. Therefore the acetic acid concentration was about 1048 mg/ml.

Used acetic acid = 65.63/1049 mg.

= 0.07 ml/synthesis wastewater 1 liter.

2) Nitrogen

The total nitrogen concentrations used in this study receive from only nutrient broth. Therefore, of all experiments the external nitrogen was not added in the synthesis wastewater. As a result, the nitrogen concentrations from nutrient broth were about 3.0 mg/l (from the experiments).

3) Phosphorus

The total phosphorus concentrations were about 2 mg/l, which prepare from KH_2PO_4 98%

The MW of KH_2PO_4 was about	=	136	
Used KH_2PO_4	=	2*(136/31)*(1/0.98)	
	=	8.8	mg.

4) The alkalinity

The alkalinity 200 mg/l as $NaHCO_3$ which prepare from $NaHCO_3$ 99.5% (the alkalinity 100 mg/l as $NaHCO_3$) and from tap water (the alkalinity 100 mg/l as $NaHCO_3$)

The MW of $NaHCO_3$ was about	=	84	
The alkalinity 100 mg/l., used $NaHCO_3$	=	(84*100)/(61*0.995)	
	=	138.39	mg.

5) Magnesium

The magnesium 0.49 mg/l., prepare from solution of $MgSO_4.7H_2O$ that have the concentration about 80g/l. (P:Mg ratio was about 1: 0.25 mole)

The magnesium used in this study	=	0.002/31	mole
	=	0.065×10^{-3}	mole
The magnesium used in this study	=	$0.25 \times 0.065 \times 10^{-3}$	mole
	=	0.49	mg

The MW. of $MgSO_4.7H_20$	=	246	
$MgSO_4.7H_20$ (l) 1 liter has Mg	=	80*(24/246)	
	=	7.8	g.
The $MgSO_4.7H_20$ used in this study	=	2.88/7.8	
	=	0.36	ml.

6) Iron

The iron 0.5 mg/l., prepare from solution of $FeCl_3.6H_2O$ that have the concentration about 15 g/l. (COD:Fe ratio was about 100: 0.5 mole)

The COD used in this study	=	100	mg/l
The iron used in this study	=	0.5	mg/l
The MW. of $FeCl_3.6H_2O$	=	270.5	
$FeCl_3.6H_2O$ (l) 1 liter has Fe	=	15*(56/270.5)	
	=	3.1	g.
The $FeCl_3.6H_2O$ (l) in this study	=	0.5/3.1	
	=	0.16	ml.

7) Calcium

The calcium 2.4 mg/l., prepare from solution of $CaCl_2$ that have the concentration about 50 g/l. (P:Ca ratio was about 1: 0.5 mole)

The phosphorus used in this study	=	0.002/31	mole
	=	$0.65x10^{-3}$	mole
The calcium used in this study	=	$0.5x0.65x10^{-3}$ mole	
	=	3.25	mg
The MW of $CaCl_2$	=	110	
$CaCl_2$ (l) 1 liter has Ca	=	50*(40/110)	
	=	18.2	g.
The $CaCl_2$ (l) in this study	=	3.25/18.2	
	=	0.18	ml.

APPENDIX C

The calculation of sludge retention time

The sludge retention time in each experiment was calculated by the amount of sludge in reactors per the amount of excess sludge from reactors. The amount of excess sludge consist of the excess sludge at the end of aerobic condition and the sludge that excess with effluent at the end of cycles. The calculation of sludge retention time as illustrated in equation (a).

$$\text{The sludge retention time} = \frac{\text{The amount of sludge in reactors}}{\text{The amount of excess sludge per day}} \quad \ldots\ldots \text{(a)}$$

As a result, the active volume of reactors was about 16.8 liters. The wastewater was added in reactors each cycle about 11.2 l/d or 22.4 l/d. Therefore, the sludge retention time was calculated by equation (b) and the result as illustrated in Table H-1 and the excess sludge was calculated in Table H-2.

$$\text{The sludge retention time} = \frac{\text{(MLVSS*16.8 L)}}{\text{[(MLVSS*waste/day) + (SS*f*(22.4-waste)/d]}} \quad \ldots \text{(b)}$$

Table H-1 The sludge retention time of this study for phase 1 to phase 5.

Phase	Reactor I (d^{-1})	Reactor II (d^{-1})
1	9.0	9.14
2	9.17	10.0
3	10.25	10.15
4	12.48	12.78
5	13.55	14.68

Table H-2 The excess sludge per day

Phases	The excess sludge per day	
	The reactor I (R1)	The reactor II (R2)
1	1.83	1.80
2	1.79	1.60
3	1.60	1.52
4	1.30	1.21
5	1.20	1.00

APPENDIX D
PHA analysis

PHA, PHB and PHV contents were determined using the methanolysis-GC method developed by Hart (1994),

1) The biomass that collected from the system was centrifuged and dried at 100 °c for at least 24 hours.
2) Weighed biomass was put into a 5 ml high pressure Wheaton vial and 2 ml of the benzoic acid solution (50 mg of benzoic acid dissolved in 100 ml of 3% sulfuric acid in methanol (v/v)) was added into each vial
3) Then, followed by another 2 ml of chloroform.
4) Vials were sealed by Teflon caps and incubated at 100 °c for 3.5 hours.
5) After the vials were cool down, distilled water added for 1 ml into every vials and the vials were shaken for about 10 minutes.
6) The layers of chloroform and sulfuric-methanol solution were separated from each other.
7) Bring 1ul from the chloroform (bottom) layer of each sample were injected in to GC equipped with a Stabilwax capillary column (inner diameter about 0.25 x 3 mn.) and attached to an FID detector.
8) The oven temperature was programmed to increase from 90 – 130 °c with rate of 20 °c/min,while the temperature of injector and detector were 160 and 200°c.
9) Pure substance of P(3HB-co-3HV) copolymer (contained 12% of 3HV)
   PHA content was defined as % TSS, i.e., the mass of PHA in the total dry weight biomass, expressed as percent. And PHA concentration and residual biomass were calculated using equations followed;

   PHA concentration = PHA content x MLSS (mg/l).

   Residual biomass = MLSS - PHA concentration (mg/l)

APPENDIX E

Table B-1 Wastewater composition of 12 selected WWTPs.

WWTP	COD:P	COD:N	BOD:P	BOD:N	Additional chemical dosing	Remark
Amersfoort	53	6	21	2.4	yes	3
Katwoude	55	12	23	5	yes	
Goor	66	12	25	4.5	no	3
Putte	83	12	32	4.5	no	
Hardenberg	72	9	27	3.4	yes[1]	
Elburg	30	9	12	3.6	yes	3
Oud-Beijerland	54	12	19	4.2	no	
Venlo	50	10	16	3.3	yes	
Waarde	55	10	23	4.2	yes[1]	
Zetten	49	7	17	2.5	no	
Maastricht-Bosscherveld	82	13	30	4.5	yes	
Haaelem-Waarderpolder	40	6	15	2.1	no [2]	4

Remark [1] Incidentally

[2] Only in the effluent of the sidestream

3 with pre- settled

4 with pre- settled and sidestream process

APPENDIX F

Table D-1 The average SVI in relation to the characteristics of the activated sludge tanks and the presence of supplementary chemical dosing.

WWTP	Selector Present	Anaerobic tank/zone	Aeration tank	Simultaneous Premoval Me/P	SVI (ml/g)
Amersfoort	Yes	Plug-flow,3 comp.	Carrousel 2000	Fe/P=0.3	89
Katwoude	Yes	Not present	Carrousel 2001	Fe/P=0.25	96
Goor	Yes	Completely mixed	Plug-flow	No	104
Putte	No	Completely mixed	Plug-flow	No	96
Hardenberg	Yes	Plug-flow	Aeration circuit	No	87
Elburg	Yes	Plug-flow,4 comp.	Carrousel	Al/P=0.4	83
Oud-Beijerland	Yes	Plug-flow,3 comp.	Carrousel	No	85
Venlo	Yes	Plug-flow,4 comp.	Carrousel	Fe/P=0.25	75
Waarde	No	Completely mixed	Schreiber	No	90
Zetten	Yes	Completely mixed	Aeration circuit	No	138
Maastricht-Bosscherveld	No	Completely mixed	Schreiber	Fe/P=0.25	63
Haaelem-Waarderpolder	Yes	Not present,plug flow in sidestream	Rotoflow	No	60

APPENDIX G

Table C-1 Aerobic and anoxic P uptake rates and the fraction of anoxic P uptake.

WWTP	Separate anoxic volume present	Aerobic P uptake (mg/gVSSs.h)	Anoxic P uptake (mg/g VSSs.h)	Fraction anoxic P uptake (%)
Amersfoort	Yes, PDN	1.2	0.7	58
Katwoude	Yes, PDN	4.6	1.6	35
Goor	Yes, PDN	4.8	1.8	38
Putte	Yes, PDN	3.4	1.5	44
Hardenberg	Yes, PDN	12.1	8.3	69
Elburg	No, aeration circuit	8	3.2	40
Oud-Beijerland	No, aeration circuit	4.5	3.6	80
Venlo	No, aeration circuit	3.2	1.6	50
Waarde	No, aeration circuit	5.2	4.5	87
Zetten	No, aeration circuit	4.8	2.8	58
Maastricht-Bosscherveld	No, aeration circuit	3	0.6	20
Haaelem-Waarderpolder	Yes, PDN	2.2	1.7	77

APPENDIX H

Table A-1 The rainfall level at Sathorn station (E 23) in 2006.

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
1-Jan-07	1	0	140.00	26.40	10.36	1.22
2-Jan-07	2	0	80.00	28.40	10.08	1.72
3-Jan-07	3	0	152.00	27.20	8.96	1.74
4-Jan-07	4	0	70.00	28.20	8.12	1.66
5-Jan-07	5	1	72.00	27.80	6.44	1.33
6-Jan-07	6	1	42.00	27.80	7.28	1.67
7-Jan-07	7	0	48.00	26.60	8.12	1.61
8-Jan-07	8	0	95.00	28.60	8.40	1.67
9-Jan-07	9	0	80.00	24.00	8.40	1.94
10-Jan-07	10	0	92.00	27.00	8.68	1.72
11-Jan-07	11	0	70.00	29.00	9.94	1.81
12-Jan-07	12	0	92.00	27.00	9.66	2.01
13-Jan-07	13	0	100.00	29.00	10.22	2.25
14-Jan-07	14	0	62.00	25.20	9.52	1.48
15-Jan-07	15	0	65.00	30.80	8.54	5.50
16-Jan-07	16	0	130.00	25.00	8.40	3.89
17-Jan-07	17	0	52.00	26.00	7.98	2.35
18-Jan-07	18	0	65.00	26.80	7.28	2.41
19-Jan-07	19	0	58.00	30.20	6.58	2.45
20-Jan-07	20	0	55.00	25.40	7.14	1.65
21-Jan-07	21	0	46.00	34.80	7.42	1.68
22-Jan-07	22	0	64.10	25.60	7.00	1.92
23-Jan-07	23	0	63.70	33.80	6.72	1.91
24-Jan-07	24	0	56.50	26.20	6.30	1.90
25-Jan-07	25	0	42.50	28.00	7.00	2.07
26-Jan-07	26	0	46.40	31.20	7.14	1.84
27-Jan-07	27	0	63.20	33.90	7.70	2.08
28-Jan-07	28	0	57.80	30.50	8.12	2.06
29-Jan-07	29	0	55.20	28.00	7.98	1.82
30-Jan-07	30	0	53.80	32.80	7.91	2.35
31-Jan-07	31	0	58.00	32.40	7.70	2.52
1-Feb-07	32	0	62.70	33.10	6.79	2.61
2-Feb-07	33	0	67.10	31.00	6.02	1.69
3-Feb-07	34	0	60.10	31.50	5.88	1.63
4-Feb-07	35	0	51.80	35.60	6.44	2.48
5-Feb-07	36	0	64.80	26.10	6.30	1.88
6-Feb-07	37	0	61.90	29.00	6.65	1.68
7-Feb-07	38	0	61.80	32.10	7.56	2.11
8-Feb-07	39	0	58.40	26.00	7.63	1.31
9-Feb-07	40	0	45.10	31.00	7.49	2.38
10-Feb-07	41	0	50.00	27.50	8.40	1.82
11-Feb-07	42	0	48.00	30.00	8.33	2.07
12-Feb-07	43	11	63.60	28.20	7.91	1.85
13-Feb-07	44	17	55.40	28.30	8.12	1.74

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
14-Feb-07	45	5.5	45.70	27.50	8.47	1.91
15-Feb-07	46	0				
16-Feb-07	47	0				
17-Feb-07	48	0				
18-Feb-07	49	26				
19-Feb-07	50	0				
20-Feb-07	51	0				
21-Feb-07	52	13				
22-Feb-07	53	0				
23-Feb-07	54	0				
24-Feb-07	55	0				
25-Feb-07	56	0				
26-Feb-07	57	0				
27-Feb-07	58	0				
28-Feb-07	59	0				
1-Mar-07	60	0	56.30	26.50	7.84	1.87
2-Mar-07	61	0	51.20	28.00	8.54	1.78
3-Mar-07	62	0	42.60	25.00	9.10	1.95
4-Mar-07	63	0	50.30	24.50	9.45	1.87
5-Mar-07	64	0	64.00	26.80	9.45	2.02
6-Mar-07	65	0	43.00	24.40	9.03	1.76
7-Mar-07	66	0	46.30	26.50	9.66	1.58
8-Mar-07	67	0	50.10	26.80	9.73	2.07
9-Mar-07	68	0	42.10	25.40	10.78	2.34
10-Mar-07	69	0	46.50	28.60	9.66	2.07
11-Mar-07	70	0	44.80	21.80	9.73	1.93
12-Mar-07	71	0	57.80	21.00	8.75	2.04
13-Mar-07	72	0	60.60	28.50	8.05	1.96
14-Mar-07	73	0	63.60	25.50	7.77	1.76
15-Mar-07	74	0				
16-Mar-07	75	0	27.56		6.97	
17-Mar-07	76	0	68.60	30.00	11.62	2.36
18-Mar-07	77	0	94.60	43.00	9.80	3.14
19-Mar-07	78	0	55.80	27.30	8.89	1.84
20-Mar-07	79	0	82.80	23.20	9.31	2.61
21-Mar-07	80	0	62.50	30.50	9.31	2.25
22-Mar-07	81	0	53.20	22.40	9.31	1.95
23-Mar-07	82	0	49.40	26.50	9.94	2.05
24-Mar-07	83	0	54.50	24.50	9.45	1.78
25-Mar-07	84	14	59.10	27.70	9.52	2.05
26-Mar-07	85	0	64.20	31.10	9.29	2.04
27-Mar-07	86	0	56.50	25.80	9.03	1.83
28-Mar-07	87	0	57.60	23.50	9.17	2.16
29-Mar-07	88	0	47.20	25.50	10.01	1.87
30-Mar-07	89	0	58.20	28.20	9.87	1.73
31-Mar-07	90	28	51.40	23.30	9.03	1.87
1-Apr-07	91	0	60.20	26.20	8.96	2.03

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
2-Apr-07	92	0	58.40	28.00	9.52	1.83
3-Apr-07	93	0	51.10	22.50	9.17	2.08
4-Apr-07	94	0	44.30	26.00	9.87	1.99
5-Apr-07	95	0	51.40	27.00	9.73	2.04
6-Apr-07	96	0	63.50	27.50	9.66	2.36
7-Apr-07	97	0	51.20	27.00	9.87	2.21
8-Apr-07	98	0	43.70	26.50	9.94	1.92
9-Apr-07	99	4	40.60	25.30	9.45	2.13
10-Apr-07	100	7.5	53.40	25.80	9.31	1.96
11-Apr-07	101	4	42.90	24.60	10.08	1.78
12-Apr-07	102	0	48.60	23.50	9.80	2.04
13-Apr-07	103	0	55.60	20.80	9.66	2.35
14-Apr-07	104	0	54.20	24.50	9.24	2.16
15-Apr-07	105	0	56.90	33.30	9.45	2.01
16-Apr-07	106	24.5	58.80	22.80	9.87	2.16
17-Apr-07	107	0	69.50	41.00	9.73	1.98
18-Apr-07	108	0	43.10	23.00	8.19	1.31
19-Apr-07	109	0	64.30	27.30	8.47	1.82
20-Apr-07	110	11.5	54.80	27.00	9.73	1.87
21-Apr-07	111	0	51.80	29.00	9.59	2.09
22-Apr-07	112	0	58.60	23.20	9.38	1.87
23-Apr-07	113	0	73.50	34.00	11.27	2.09
24-Apr-07	114	0	80.80	30.00	9.94	2.20
25-Apr-07	115	0	67.70	31.00	15.05	2.71
26-Apr-07	116	0	56.70	28.60	11.62	2.14
27-Apr-07	117	0	71.90	43.00	11.62	2.19
28-Apr-07	118	0	68.40	51.70	13.51	2.47
29-Apr-07	119	0.5	75.50	49.50	11.34	2.80
30-Apr-07	120	0	57.70	36.30	10.15	1.92
1-May-07	121	8.5	57.20	36.30	10.50	2.41
2-May-07	122	0.5	59.00	32.00	10.50	2.07
3-May-07	123	0	61.50	24.80	9.94	1.51
4-May-07	124	0	56.20	26.80	12.25	2.21
5-May-07	125	0	59.80	31.60	9.94	2.35
6-May-07	126	0	41.40	23.40	10.08	2.33
7-May-07	127	1.5	64.10	30.80	10.01	2.78
8-May-07	128	0	80.80	26.60	9.38	1.87
9-May-07	129	0	60.80	30.60	12.04	2.38
10-May-07	130	0	94.00	27.90	13.02	5.18
11-May-07	131	0	87.20	28.10	12.18	2.69
12-May-07	132	0	74.80	29.40	12.46	2.94
13-May-07	133	0	144.20	38.80	12.74	2.92
14-May-07	134	0	82.50	25.20	12.46	2.66
15-May-07	135	0	76.50	28.50	8.33	1.79
16-May-07	136	0	72.20	26.40	10.29	2.12
17-May-07	137	0	116.80	27.30	12.25	2.57
18-May-07	138	0	86.00	31.80	10.92	2.24

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
19-May-07	139	6.5	51.10	28.40	6.79	1.38
20-May-07	140	11.5	69.70	34.60	10.50	2.03
21-May-07	141	12	81.90	34.50	8.05	2.17
22-May-07	142	0	72.00	39.80	9.80	2.08
23-May-07	143	1	127.20	51.00	12.32	2.86
24-May-07	144	1	93.80	56.70	14.56	2.45
25-May-07	145	0	132.80	51.00	14.56	2.90
26-May-07	146	0	92.20	54.00	14.63	2.94
27-May-07	147	11	136.00	66.00	15.54	4.07
28-May-07	148	0	72.20	36.90	13.58	2.42
29-May-07	149	0	80.50	45.00	12.46	2.30
30-May-07	150	0	85.00	37.50	13.51	2.42
31-May-07	151	0	72.30	29.30	10.01	2.45
1-Jun-07	152	0	86.00	30.50	7.70	1.97
2-Jun-07	153	3.5	80.50	33.00	10.36	1.79
3-Jun-07	154	0	99.50	44.40	14.42	3.27
4-Jun-07	155	0	100.80	43.50	12.53	3.90
5-Jun-07	156	29.5	64.20	26.20	11.34	2.72
6-Jun-07	157	0	70.20	31.60	11.83	2.84
7-Jun-07	158	29	70.50	27.50	7.49	2.23
8-Jun-07	159	0	90.00	39.20	10.43	2.87
9-Jun-07	160	2	78.00	43.50	10.78	2.06
10-Jun-07	161	11	83.00	46.10	12.88	2.32
11-Jun-07	162	11	93.30	39.00	12.18	2.87
12-Jun-07	163	0.5	76.30	32.20	11.48	2.90
13-Jun-07	164	0	129.80	46.50	12.74	4.29
14-Jun-07	165	10.5	164.80	63.00	14.21	5.04
15-Jun-07	166	11.5	80.50	35.60	11.97	2.54
16-Jun-07	167	37	89.80	42.00	12.74	2.44
17-Jun-07	168	37	67.00	30.80	9.87	2.56
18-Jun-07	169	56.5	63.10	24.80	10.78	2.53
19-Jun-07	170	0	48.00	28.00	5.04	1.97
20-Jun-07	171	9	69.80	31.00	8.75	2.11
21-Jun-07	172	11	141.80	73.00	9.59	4.67
22-Jun-07	173	5.5	134.20	69.00	11.62	5.13
23-Jun-07	174	15	155.80	79.50	12.88	6.02
24-Jun-07	175	110.5	148.20	33.80	6.09	4.24
25-Jun-07	176	31	102.50	39.80	8.40	4.92
26-Jun-07	177	50.5	62.20	27.80	6.57	2.39
27-Jun-07	178	13.5	210.00	55.50	7.91	3.72
28-Jun-07	179	0	136.50	66.00	12.04	4.70
29-Jun-07	180	0	309.00	129.00	13.30	8.78
30-Jun-07	181	7	117.80	45.00	11.90	3.19
1-Jul-07	182	13.5	113.00	45.00	12.04	2.43
2-Jul-07	183	20	86.50	34.50	7.63	2.70
3-Jul-07	184	10	73.40	31.80	7.70	2.60
4-Jul-07	185	0	105.50	36.00	10.85	3.26

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
5-Jul-07	186	23	81.50	49.50	11.62	2.50
6-Jul-07	187	0	80.20	34.60	8.89	2.63
7-Jul-07	188	14	176.20	55.90	8.96	6.22
8-Jul-07	189	0	97.20	44.20	11.20	2.96
9-Jul-07	190	0	95.50	40.20	12.74	2.83
10-Jul-07	191	8.5	99.00	35.60	11.83	2.53
11-Jul-07	192	11.5	81.50	29.20	9.31	2.12
12-Jul-07	193	0	98.20	37.50	12.18	2.70
13-Jul-07	194	0	80.80	36.80	10.43	2.34
14-Jul-07	195	1.5	141.80	55.50	15.75	3.75
15-Jul-07	196	1.5	160.50	60.00	13.65	4.31
16-Jul-07	197	0	120.50	48.00	12.79	4.01
17-Jul-07	198	0	118.20	44.20	12.53	3.93
18-Jul-07	199	0	100.80	38.20	13.09	2.34
19-Jul-07	200	0	102.00	40.90	14.21	3.06
20-Jul-07	201	0	99.20	37.10	14.28	2.63
21-Jul-07	202	11	109.00	47.20	13.72	3.62
22-Jul-07	203	0	133.20	46.50	13.44	3.98
23-Jul-07	204	0	108.80	39.00	12.32	3.26
24-Jul-07	205	0	87.20	38.20	12.18	2.40
25-Jul-07	206	0	92.80	39.00	12.32	3.75
26-Jul-07	207	0	102.80	42.00	12.95	3.78
27-Jul-07	208	0	95.00	35.60	13.72	2.82
28-Jul-07	209	0	110.80	34.60	13.65	3.46
29-Jul-07	210	0	94.20	40.80	14.63	2.95
30-Jul-07	211	0	103.20	43.10	16.94	2.34
31-Jul-07	212	43	104.00	46.50	14.84	5.88
1-Aug-06	213	46	111.80	39.80	10.22	6.54
2- Aug-06	214	2	87.20	37.20	10.29	5.45
3- Aug-06	215	0	102.00	46.90	12.11	4.01
4- Aug-06	216	13	109.50	43.50	13.44	4.10
5- Aug-06	217	0	85.50	38.60	8.89	2.56
6- Aug-06	218	0	87.80	39.00	9.38	2.73
7- Aug-06	219	0	98.20	41.20	11.69	3.21
8- Aug-06	220	0	109.00	58.50	12.04	5.08
9- Aug-06	221	0	90.80	39.00	14.35	3.05
10- Aug-06	222	0	85.80	29.60	13.23	2.40
11- Aug-06	223	0	98.50	30.80	13.30	2.34
12- Aug-06	224	0	77.00	29.20	12.53	2.40
13- Aug-06	225	0	196.50	41.20	11.97	4.42
14- Aug-06	226	4.5	96.00	30.00	12.04	2.95
15- Aug-06	227	0.5	68.60	29.20	12.04	2.53
16- Aug-06	228	1	108.00	34.50	12.04	3.37
17- Aug-06	229	1	98.50	43.20	12.25	3.37
18- Aug-06	230	0	86.50	34.80	12.32	2.79
19- Aug-06	231	0	82.80	35.20	12.11	2.53
20- Aug-06	232	19.5	89.00	43.10	11.76	2.82

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
21- Aug-06	233	20	99.80	41.10	10.29	3.05
22- Aug-06	234	0.5	91.00	36.40	9.59	2.89
23- Aug-06	235	14	87.00	40.10	13.09	2.34
24- Aug-06	236	0	90.00	33.80	9.59	1.44
25- Aug-06	237	0	76.00	30.80	10.57	2.53
26- Aug-06	238	0	63.50	28.20	12.11	2.34
27- Aug-06	239	0	65.60	33.00	12.04	3.45
28- Aug-06	239	1	99.80	42.80	12.39	4.36
29- Aug-06- Aug-06	239	16.5	77.20	33.00	13.58	3.17
30- Aug-06	239	27	96.20	30.80	10.64	1.91
31- Aug-06	239	11	77.20	33.00	9.38	2.37
1-Sep-06	239	0	72.20	38.60	11.06	3.56
2-Sep-06	245	0	92.50	29.80	12.60	2.85
3-Sep-06	246	0	62.20	26.80	12.11	2.95
4-Sep-06	247	0	79.80	33.80	12.04	3.24
5-Sep-06	248	0	91.20	33.40	12.18	3.21
6-Sep-06	249	11	85.50	27.80	12.81	3.05
7-Sep-06	250	60	72.20	32.20	10.15	2.91
8-Sep-06	251	39.5	71.20	40.90	7.21	2.36
9-Sep-06	252	35	67.00	29.20	8.33	2.32
10-Sep-06	253	95	76.80	42.00	10.78	2.60
11-Sep-06	254	85	68.20	27.80	10.57	3.26
12-Sep-06	255	11.5	68.00	27.00	11.41	2.51
13-Sep-06	256	27	72.50	28.20	9.73	2.45
14-Sep-06	257	98	59.20	32.20	7.49	2.70
15-Sep-06	258	94	65.50	27.50	6.37	2.08
16-Sep-06	259	0	72.50	27.00	8.54	2.39
17-Sep-06	260	0.5	64.80	28.00	7.42	2.08
18-Sep-06	261	0	69.80	26.50	7.00	2.29
19-Sep-06	262	0	58.80	25.80	8.61	2.08
20-Sep-06	263	0	57.50	25.00	11.34	2.14
21-Sep-06	264	0	73.00	25.50	8.33	2.36
22-Sep-06	265	0	224.00	46.50	13.09	10.20
23-Sep-06	266	0	59.80	25.20	11.83	1.92
24-Sep-06	267	0	75.80	32.50	8.26	2.26
25-Sep-06	268	0	84.50	36.40	10.36	2.32
26-Sep-06	269	25	70.80	28.80	9.94	2.23
27-Sep-06	270	0	62.50	28.50	7.77	1.95
28-Sep-06	271	0	61.00	28.80	9.24	2.14
29-Sep-06	272	0	71.20	28.20	10.08	2.06
30-Sep-06	273	0	83.80	27.20	11.48	2.53
1-Oct-06	274	0	81.80	26.00	11.76	2.65
2-Oct-06	275	10.5	78.00	29.80	11.83	2.60
3-Oct-06	276	10.5	84.20	26.20	10.99	2.29
4-Oct-06	277	0	93.80	27.00	11.83	2.34
5-Oct-06	278	40	100.80	32.20	16.40	2.96
6-Oct-06	279	0	80.50	30.00	8.54	3.02

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
7-Oct-06	280	0	83.50	31.80	10.29	2.81
8-Oct-06	281	2	83.50	25.60	9.80	2.77
9-Oct-06	282	30	80.50	32.60	10.08	2.43
10-Oct-06	283	153	93.00	29.60	8.75	3.02
11-Oct-06	284	0	73.00	26.00	5.67	2.19
12-Oct-06	285	72.5	64.50	24.20	4.34	1.44
13-Oct-06	286	34	60.20	25.00	6.09	1.77
14-Oct-06	287	54	93.20	39.00	9.24	1.78
15-Oct-06	288	42.5	57.50	27.80	9.52	2.82
16-Oct-06	289	3	58.00	26.20	8.68	2.31
17-Oct-06	290	0	73.20	30.40	9.03	2.73
18-Oct-06	291	37	64.20	24.80	9.80	2.38
19-Oct-06	292	0	60.50	26.00	11.41	1.94
20-Oct-06	293	0	81.50	30.00	8.68	2.23
21-Oct-06	294	0	66.40	24.00	9.66	2.21
22-Oct-06	295	0	63.90	47.60	9.73	3.61
23-Oct-06	296	0	65.20	23.80	8.61	2.09
24-Oct-06	297	0	61.00	21.80	9.80	2.15
25-Oct-06	298	0	67.20	21.00	9.59	2.15
26-Oct-06	299	0	46.20	23.00	9.80	2.00
27-Oct-06	300	0	70.50	23.00	9.94	2.00
28-Oct-06	301	0	76.20	22.00	10.64	2.12
29-Oct-06	301	0	60.10	24.50	10.15	2.27
30-Oct-06	303	0	46.20	22.20	9.45	2.21
31-Oct-06	304	0	64.20	21.70	9.59	2.75
1-Nov-06	305	0	66.20	22.20	9.17	1.99
2-Nov-06	306	0	45.50	22.10	9.10	1.74
3-Nov-06	307	0	48.20	20.80	7.84	3.07
4-Nov-06	308	0	46.80	22.80	6.51	1.16
5-Nov-06	309	0	46.70	20.50	6.65	1.37
6-Nov-06	310	0	46.20	23.50	6.44	1.41
7-Nov-06	311	0	44.10	20.10	7.14	1.59
8-Nov-06	312	0	32.50	20.00	8.12	1.55
9-Nov-06	313	0	48.30	20.10	7.84	1.14
10-Nov-06	314	0	60.90	29.70	9.66	2.05
11-Nov-06	315	0	64.30	36.00	9.93	1.65
12-Nov-06	316	0	48.90	20.20	9.03	1.88
13-Nov-06	317	0	42.40	20.40	7.28	1.70
14-Nov-06	318	0	48.40	20.10	7.28	1.61
15-Nov-06	319	0	36.40	20.10	7.91	1.73
16-Nov-06	320	0	44.80	21.00	8.19	1.71
17-Nov-06	321	0	56.10	24.90	8.26	1.68
18-Nov-06	322	0.5	55.30	24.60	7.84	1.79
19-Nov-06	323	0.5	52.80	37.80	8.61	2.20
20-Nov-06	324	16	61.70	25.80	8.26	2.06
21-Nov-06	325	0	46.50	22.80	8.54	1.77
22-Nov-06	326	5.5	51.20	24.00	8.26	1.80
23-Nov-06	327	0	50.50	24.40	7.77	1.69

Date	Days	rainfall day 2006 (mm.)	COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)
24-Nov-06	328	0	46.00	28.50	7.35	1.65
25-Nov-06	329	0	55.30	22.20	7.70	1.67
26-Nov-06	330	0	50.50	26.40	8.12	1.70
27-Nov-06	331	0	51.20	23.60	8.96	1.76
28-Nov-06	332	0	52.50	25.70	7.77	1.78
29-Nov-06	333	0	55.00	26.80	7.07	2.09
30-Nov-06	334	0	58.50	28.70	8.89	1.73
1-Dec-06	335	0	54.20	26.80	8.68	1.82
2-Dec-06	336	0	48.50	24.70	8.54	1.49
3-Dec-06	337	0	47.60	22.00	8.33	1.33
4-Dec-06	338	0	50.30	24.60	8.61	1.85
5-Dec-06	339	0	45.70	21.90	8.61	1.89
6-Dec-06	340	3	39.00	19.10	8.19	1.76
7-Dec-06	341	3.5	49.40	23.70	7.91	1.30
8-Dec-06	342	0.5	31.30	15.30	7.84	1.63
9-Dec-06	343	0	44.20	19.90	7.49	2.58
10-Dec-06	344	0	39.70	17.10	7.70	1.49
11-Dec-06	345	0	40.50	17.80	7.14	1.79
12-Dec-06	346	0	65.60	29.30	10.01	1.98
13-Dec-06	347	0	66.30	28.00	9.52	1.89
14-Dec-06	348	0	60.00	21.00	8.05	1.44
15-Dec-06	349	0	57.00	31.00	8.82	1.70
16-Dec-06	350	0	64.90	29.00	9.38	1.44
17-Dec-06	351	0	59.50	23.00	8.68	1.60
18-Dec-06	352	0	61.90	30.00	9.38	1.89
19-Dec-06	353	0	64.40	17.00	8.75	1.64
20-Dec-06	354	0	67.50	21.00	8.96	1.84
21-Dec-06	355	0	66.70	16.00	8.75	1.08
22-Dec-06	356	0	73.60	26.00	4.94	1.42
23-Dec-06	357	0	79.80	26.00	8.26	2.03
24-Dec-06	358	0	85.00	41.00	10.78	2.01
25-Dec-06	359	0	85.00	32.00	9.52	1.39
26-Dec-06	360	0	71.50	30.80	10.01	1.82
27-Dec-06	361	0	74.80	29.20	9.45	1.60
28-Dec-06	362	0	82.20	35.20	9.10	1.64
29-Dec-06	362	0	86.20	38.20	7.49	2.73
30-Dec-06	363	0	77.00	30.40	8.40	2.27
31-Dec-06	364	0	88.00	33.40	8.05	2.40

Table A-1shows the rain fall levels of Sathon station between 1 Jun 05 to 31 Dec 06, which indicated that consistent of the rain fall level in the period of this study. As a result shows the rain fall levels, COD, TKN, and phosphorus concentrations as illustrated in Figure A-1.

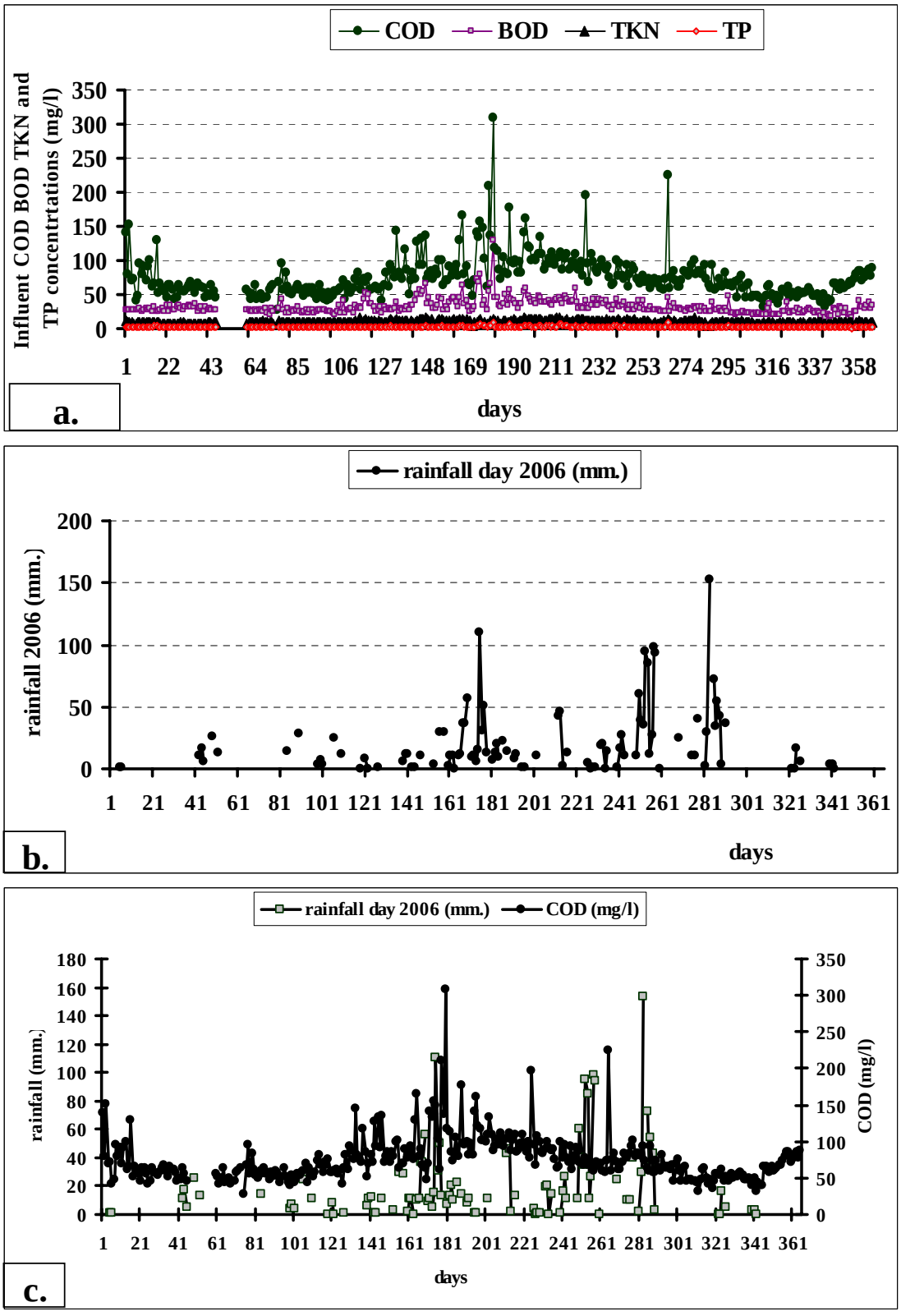


Figure A-1 The relationship between influent COD, BOD, TKN and TP concentration and rainfall level in Sathorn station in 2006.

APPENDIX I

Comparison between CASS and AS configuration process

For the conventional activated sludge system described in below, calculate the production of biological solids (von Sperling M. and de Lemos Chernicharo C.A., 2005).

$Q = 100{,}000\ m^3/d$	$\theta_c = 10$ days	$Y = 0.7$
$S_0 = 49$ mg/l	$X_v = 2000$ mg/l	$K_d = 0.09\ d^{-1}$
$S = 17$ mg/l	$V = 3{,}675\ m^3$	VSS/SS = 0.8, $f_b = 0.72$

Q	=	influent flow (m^3/d)
θ_c	=	the sludge age (d)
Y	=	yild coefficient (gVSS produce per gBOD removed)
S_0	=	influent substrate concentration (total BOD) (mg/L or g/m^3)
S	=	effluent substrate concentration (total BOD) (mg/L or g/m^3)
X_v	=	volatile suspended solid (mg/L)
K_d	=	endogenous respiration coefficient (d^{-1})
V	=	reactor volume (m^3)
VSS/SS	=	MLVSS/MLSS ratio
f_b	=	biodegradable fraction of MLVSS (X_b / X_v)

The typical values of Y and K_d are

Y = 0.5-0.7 gVSS / $gBOD_5$ removed

K_d = 0.06-0.1 gVSS / gVSS.d

Solution

(a) Calculation of the BOD load removed

$S_r = Q (S_0-S)$

$= 100{,}000\ m^3/d * [(49-17)\ g/m^3 * 10^{-3}\ kg/g]$

$= 3{,}200$ kg BOD/d

(b) $P_{xv} = Y\ Q\ (S_0-S) - Kd\ f_b\ X_v\ V$

= (0.7* 100,000 m^3/d) * [(49-17) g/m^3* 10^{-3} kg/g]– [(0.09 d^{-1} *0.7 * 2,000 g/m^3 * 3,675 m^3 * 10^{-3} kg/g)]

= 2,240 – 661.5 kg VSS/d

= 1,579 kg VSS/d

P_x = P_{xv} / (VSS/SS)

= (1,579 kg VSS/d) / 0.8

= 1,974 kgSS / d

(c) P_{inf} = (2 mg/L)* (100,000 m^3/d)

= 2x10^8 mg/d

= 2x10^5 kg/d

(d) Phosphorus content in biomass for activated sludge about 1-3% (Ref)

Therefore the phosphorus content in biomass use in this study is 2%

P_{syn} = (0.02) * (1,579 kg VSS/d)

= 31.58 kg/d

(e) P_{eff} = P_{inf}- P_{syn}

= (2x10_5 kg/d) – (31.58 kg/d)

= (199,968 kg/d) (1,000 mg/kg) (d/100,000) (m^3/1000L)

= 1.99 mg/L

Note; 1) if the phosphorus content in biomass is 1%

Hence, the effluent phosphorus concentration is 2.0 mg/L, and

2) if the phosphorus content in biomass is 1.5%

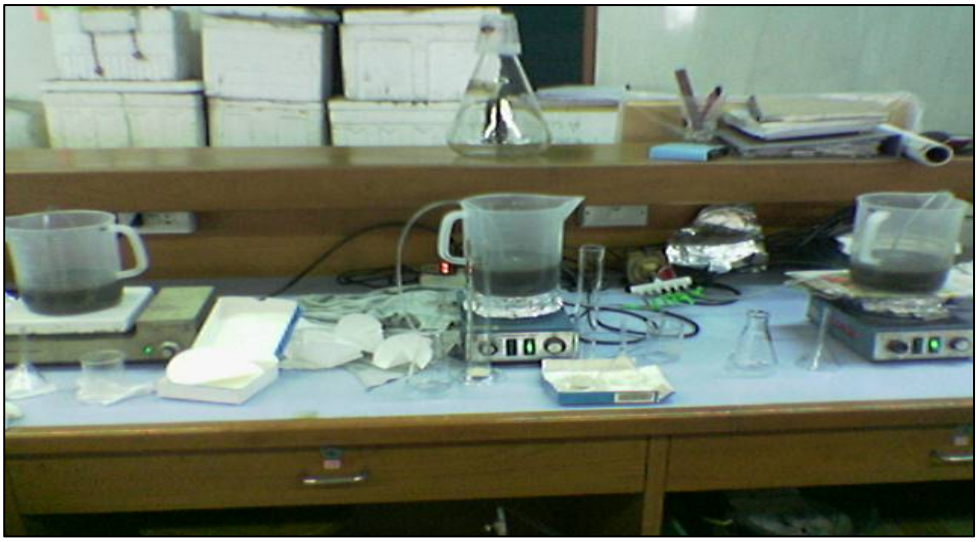
Hence, the effluent phosphorus concentration is 2.0 mg/L.

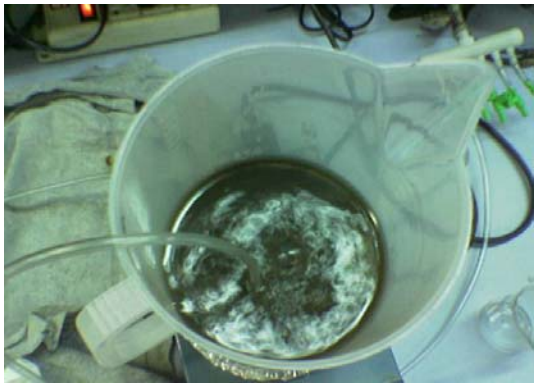
As a result, the CASS configuration process had been produced the lower effluent phosphorus concentration than the AS configuration process.

APPENDIX J

Batch Test

The batch test sets of this study as illustrated in Figure J-1 and J-2.





(a) (b)

Figure J-2 batch test set in (a) aerobic condition and (b) anaerobic condition

The batch test set configuration as illustrated in Figure J-3 to J-6

Batch Test set 1

Anaerobic Sludge

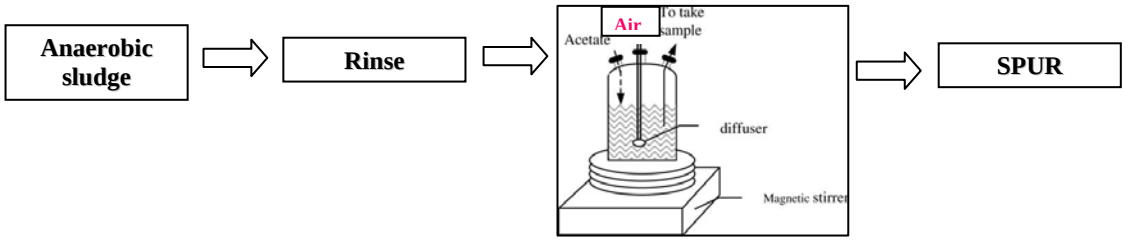


Figure J-3 the batch test 1 of anaerobic sludge.

Aerobic Sludge

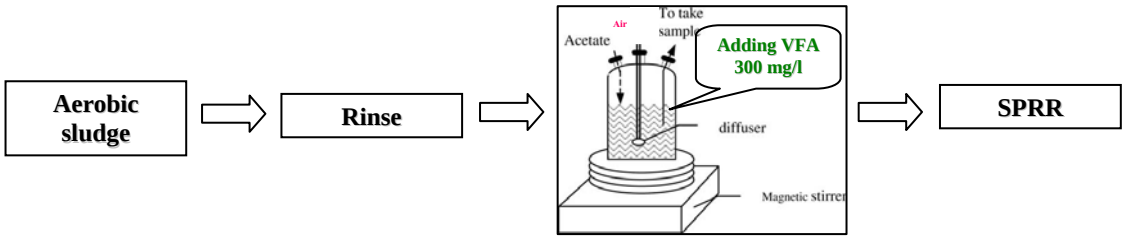


Figure J-4 the batch test 1 of aerobic sludge.

Batch Test set 2

Anaerobic Sludge

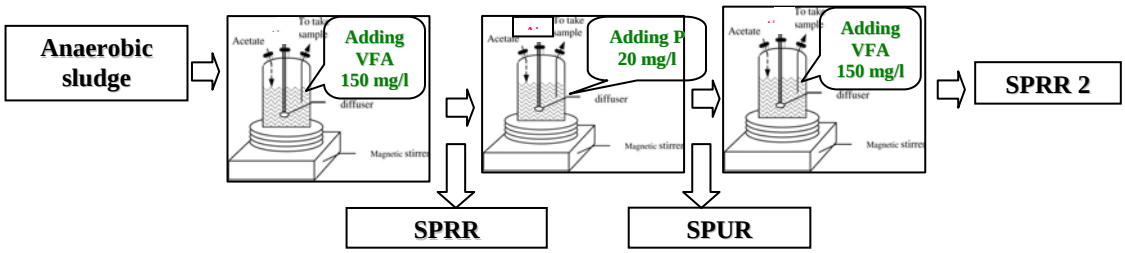


Figure J-5 the batch test 2 of anaerobic sludge.

Aerobic Sludge

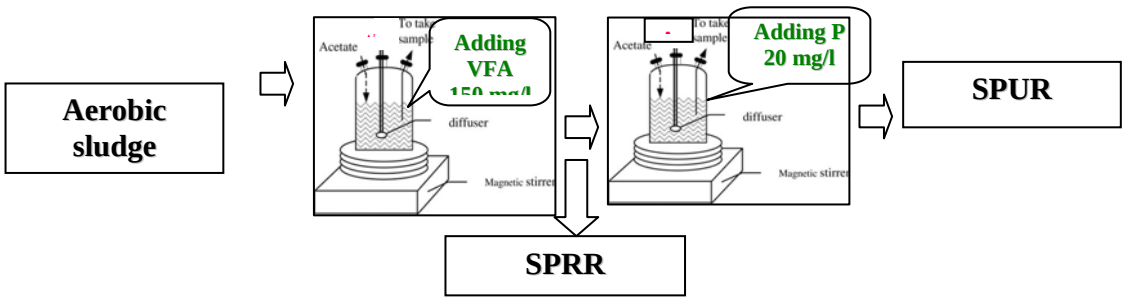


Figure J-6 the batch test 2 of aerobic sludge.

BIOGRAPHY

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