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INVESTIGATION OF ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL (EBPR) PROCESS PERFORMANCE AT SNJ WASTEWATER TREATMENT PLANT (IVAR)

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Abstract

This study has investigated the efficiency of phosphorus (P) removal and optimization the function of the Enhanced Biological Phosphorus Removal (EBPR) at SNJ (Sentralrenseanlegg Nord-Jæren), owned by IVAR (Interkommunalt Vann, Avløp og Renovasjon) at Mekjarvik, Randaberg. During this study, the wastewater was characterized in terms of the relevant substances for EBPR. In addition, tests on primary sludge fermentation and its effect on EBPR were performed. An overview of phosphate release in the bioreactor and in batch tests was performed. Also, measurements of the sludge blanket level in settling tanks were done.

The main results of this project were that the primary sludge had a potential for fermentation of filtered Chemical Oxygen Demand (COD_{filt}) to VFA (Volatile Fatty Acids) for stimulation of phosphate release and P removal by the EBPR sludge. The conclusion of this test is the primary sludge produced a good substrate for EBPR. The average endogenous and stimulated phosphate release rates in the bioreactor L1 is 1.3 mg P/g VSS h^{-1} (Volatile Suspended Solids per hour), at temperature 9-10°C and pH 6-7 respectively. This is in category level **moderate** based on the literature values. The influent average ratio of COD_{filt}:PO_4-P (dissolved P) is 30 g/g which is referred to as near optimal for EBPR. The average treatment efficiency for phosphate in the EBPR plant was a reduction from 1.3 mg/l in the influent to 1.08 mg/l in the effluent. Based on data from SNJ, the average treatment efficiency for P removal is 44.9 %. The main reasons for this low removal were inefficient anaerobic tanks due to oxygen intrusion and PO_4-P release (secondary release) in the settling tanks due to anaerobic conditions in the sludge caused by unfavourable hydraulic conditions, and probably too low capacity on the sludge scrapers.

The batch test in the laboratory shows the biological process behave as expected which is phosphate release in the anaerobic reactor and uptake in the aerobic reactor. The conclusion is the sludge has the potential of high phosphate removal if the conditions are optimal. The sludge blanket level in settling tanks was measured and the average SVI (Sludge Volume Index) level was 90.4 mg/l, which indicate good settling and high-quality effluent. But because of high sludge blanket in the settling tank, there was secondary phosphate release and reduced P removal efficiency. Further studies should focus on improving the conditions for EBPR, which mean optimization of the anaerobic tanks and reducing the sludge level in the settling tanks.

Keywords: Wastewater treatment; biological phosphorus removal; EBPR; Primary sludge; VFA; Settling tank.

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Abbreviations

BOD Biological Oxygen Demand
BSCOD Biodegradable soluble Chemical Oxygen Demand
COD Chemical Oxygen Demand
DO Dissolved Oxygen
EBRP Enhanced Biological Phosphorus Removal
F/M Food/Microorganism
F-Nss Fraction Nitrogen suspended
F-Pss Fraction Phosphorus suspended
GAO Glycogen Accumulating Organisms
HAc Acetic acid
HCl Hydrochloric acid
HRT Hydraulic Retention Time
HPr Propionic acid
IVAR Interkommunalt Vann, Avløp og Renovasjon
LCFA Long Chain Fatty Acids
MLSS Mixed Liquor Suspended Solids
N Nitrogen
NH_4-N Ammonium, as N
OHO Ordinary Heterotrophic Organisms
P Phosphorous
PAO Polyphosphate Accumulating Organisms
PHA Poly-hydroxy-alkanoate
PHB Poly-b-hydroxyburate
PO_4-P: Phosphate, as Posphorus
PST Primary Settling Tanks
RAS Return Activated Sludge
RBCOD Readily Biodegradable COD
SNJ Sentralrenseanlegg Nord-Jæren
SST Secondary Settling Tanks
SVI Sludge Volume Index
TDS Total Dissolved Solids
TFO Tetrad Forming Organisms
TOT N Total Nitrogen
TOT P Total Phosphorus
TS Total Solids
TSS Total Suspended Solids
TVS Total Volatile Solids
VFA Volatile Fatty Acids
VSS Volatile Suspended Solids
WWTP Wastewater Treatment Plant

1. Introduction

The continuous increasing production of municipal wastewater with increasing population is one of the main problems in water pollution. Because of this, eutrophication has become a significant water quality problem. To prevent eutrophication, phosphorus removal from wastewater has become a key strategy. EBPR has been applied in many wastewater treatment plants (WWTPs). EBPR is a sustainable, economical, and environmentally friendly method for phosphorus removal.

IVAR SNJ WWTP has implemented biological treatment with EBPR instead of a chemical treatment since 2017. The implementation of EBPR compliance with discharge restriction for phosphorus is 1 mg/l (Forurensningsforskriften, 2005), while SNJ has no P limit, only BOD (Biological Oxygen Demand) and COD limits. IVAR will, however, remove and recover phosphorus for recycling as fertilizer.

The successful operation of EBPR depends on environmental factors, process operational factors, and the wastewater composition. This thesis is based on studies of some of these factors at SNJ.

1.1 Scope Of Work

This study was a project with IVAR SNJ WWTP at Mekjarvik. IVAR is a Norwegian public company that constructs and operates municipal facilities for solid waste, water, and wastewater. In this study, the EBPR process at SNJ was studied in laboratory scale and full scale with respect to factors affecting the process performance at the plant. Process analyses were done in a process laboratory at IVAR SNJ. The wastewater treatment process at SNJ is presented in figure 1.1.
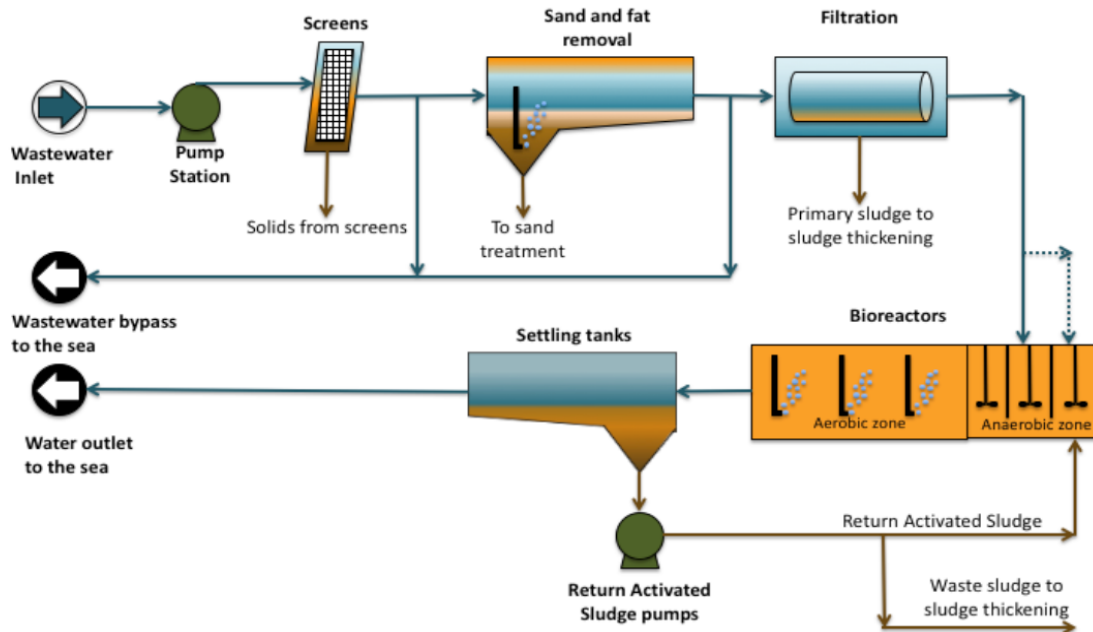
Figure 1.1: Wastewater treatment process at SNJ (Adopted figure from Egeland, 2018)

1.2 Objectives

The main objective of this master thesis was to investigate the EBPR and the factors that affects the process performance at SNJ. Furthermore, this study included laboratory testing of the potential for the system to remove phosphorus in wastewater.

- The activity of the EBPR in the bioreactors
- The endogenous phosphate release from EBPR sludge in anaerobic batch test
- The fermentation of primary sludge for VFA production
- Full-scale and laboratory-scale for analyses of phosphate
- Settling tank sludge level measurements

1.3 Thesis Outline

This master thesis titled is "Investigation of Enhanced Biological Phosphorus Removal (EBPR) Process Performance At SNJ Wastewater Treatment Plant (IVAR)" and divided into seven chapters.

1. Introduction
2. Theory and Background
3. Materials and Methods
4. Results
5. Conclusion
6. Recommendations for further research
7. References

Appendixes are included to present supporting of the whole study.

2. Theory and Background

This chapter describes the theoretical basis for characteristics of wastewater, EBPR overview, and factors affecting the process. The development of EBPR from previous studies is also presented. Furthermore, the biological process in the SNJ WWTP is presented. Based on this literature review and theoretical background, the knowledge gaps are well defined as specific objectives of this current study.

2.1 Characteristic of Wastewater

Characteristic of Norwegian wastewater is typically cold, low in nutrients and diluted. It is because of the high amount of precipitation and runoff during wastewater transportation and combined sewers. Characterization of wastewater will vary from one place to another. This experiment used wastewater from Stavanger area which enters the SNJ WWTP.

Based on Ødegaard (1999), the treatment plants in the Nordic countries (Norway, Sweden and Finland) have wastewater that can be characterised as having a high fraction of organic matter on suspended form, a considerable fraction of P on suspended form and a surprisingly high fraction on the nitrogen (N) on suspended form. Based on those characteristics, wastewater treatment can economically be achieved by enhancing particle separation in primary treatment, either by coarse filtration or by coagulation (Ødegaard, 1999). Table 2.1 adopted from Ødegaard (1999) and show fractious of N and P in the wastewater in Scandinavia.

Table 2.1: Average value N and P in raw wastewater from Scandinavian plants

Country	N	Tot N	NH$_4$-N	F-N$_{SS}$[1]	Tot P	PO$_4$-P	F-P$_{SS}$[2]
Sweden	17	33,1 $\pm$8,1	24,4 $\pm$7,6	0,28 $\pm$0,13	6,14 $\pm$1,65	3,26 $\pm$1,42	0,49 $\pm$0,15
Norway	12	22,0 $\pm$6,2	13,7 $\pm$4,2	0,29 $\pm$0,08	3,00 $\pm$1,12	1,10 $\pm$0,62	0,65 $\pm$0,09
Finland	7	43,8 $\pm$10,4	28,7 $\pm$7,6	0,33 $\pm$0,07	7,47 $\pm$1,34	3,29 $\pm$1,36	0,56 $\pm$0,19

[1] Based on the assumption that the organic N is suspended
[2] Based on the assumption that the soluble P is equal to soluble PO$_4$-P

Note:
Tot N: Total N; NH$_4$-N: Ammonium, as N; F-Nss: Fraction N suspended; Tot P: Total P; PO$_4$-P: Phosphate, as P; F-Pss: Fraction P suspended.

Table 2.2 adapted from Ødegaard et al., (2014), shown the average values on organic matter in raw wastewater from Scandinavian WWTPs.

Table 2.2: Average value on organic matter in raw wastewater from Scandinavian plants

Country	N[1]	SS	COD	COD_f	Fract. COD_{SS}	BOD	BOD_f	Fraction BOD_{SS}	BOD/COD Tot	Filtr
Sweden	17	243	477	157	0,68	171	63	0,66	0,32	0,38
		+87	+123	+79	+0,10	+72	+47	+0,12	+0,12	+0,10
Norway	12	143	233	81	0,66	113	33	0,71	0,48	0,48
		+39	+69	+30	+0,11	+28	+9	+0,11	+0,21	+0,17
Finland	7	378	559	164	0,71	266	81	0,71	0,46	0,43
		+144	+161	+22	+0,06	+78	+27	+0,06	+0,08	+0,05

[1]Number of plants included

The characteristics of wastewater varies according to season, hour and day (Ødegaard et al., 2014). This variation can influence wastewater composition in the EBPR process and can give the EBPR process operational problems. The hourly and daily analysis of the wastewater and compounds subsequent can give important information about the wastewater characteristics and conditions. Figure 2.1 is to illustrate the general flow in wastewater on an hourly basis.
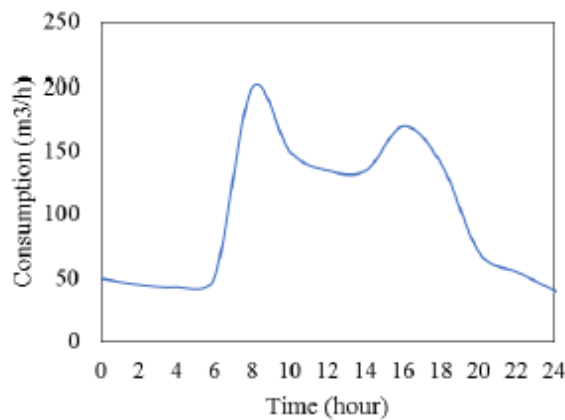
Figure 2.1: Illustrated the general flow in wastewater on an hourly basis (adapted from Ødegaard et al.,2014).

2.2   Phosphorus

Phosphorus is an essential nutrient for algae growth, agricultural crops and other biological organisms (Tchobanoglous et al., 2014). Sources of phosphorus are mainly municipal and industrial wastewater and agriculture. Phosphorus in wastewater can be categorized into two fractions: dissolved phosphorus and particulate. In aqueous solution, phosphorus can be found in such as orthophosphate, polyphosphate, and organic phosphate (Tchobanoglous et al., 2014). The nutrients causing excessive algae growth and later oxygen depletion and finally killing fish and other aquatic life.

The most important nutrients causing eutrophication of lakes and natural waters is Phosphorus and Nitrogen. Eutrophication is a global problem in aquatic environments, which means the overload of nutrients to the water. A key factor in preventing eutrophication of water is by controlling phosphorus discharged from municipal and industrial wastewater treatment plants and agricultural land.

Removal of P from wastewater is mainly based on the conversion of dissolved phosphates into suspended P, which then is separated from the water. P removal is typically by chemical and biological methods or a combination of them (Morse et al., 1998). EBPR is one method used to reduce P in wastewater that has shown to be environmentally compatible and economical.

Figure 2.2 show from the survey that plants data for total P versus fraction suspended P in Scandinavian wastewater. The figure show that Norwegian wastewater is lowest in the concentration of total P and have the highest fraction of suspended P compared to Sweden and Finland.
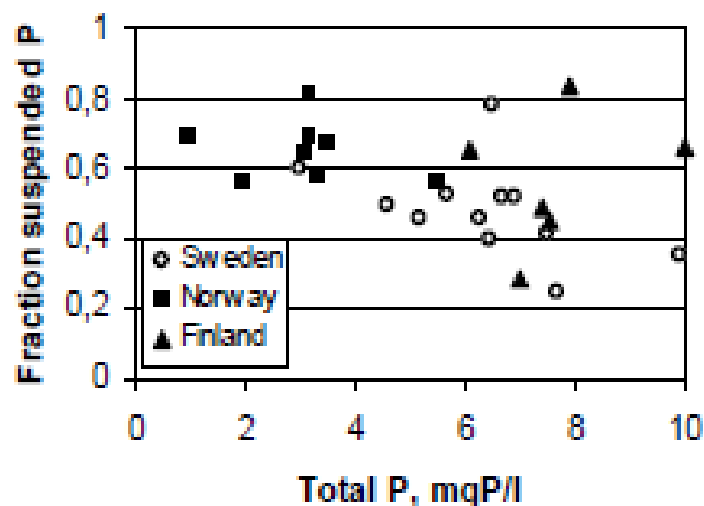
Figure 2.2: Fraction of P on suspended form in Scandinavian wastewater (adopted from Ødegaard et al., 2014)

2.2.1 Phosphorus removal by chemical methods

Phosphorus removal by chemical precipitation is divided into three steps: coagulation, flocculation, and separation. The principle is the transformation of soluble phosphorus to particulate P and the removal of this by sedimentation.

Typically, cations used for precipitation of phosphorus from wastewater are Aluminium (Al), Iron (Fe), and Calcium (Ca) (Reddy et al., 1998). All of these three cations will produce insoluble precipitates with orthophosphate. Soluble orthophosphate reacts with the cations and the primary phosphorus species affected by chemical removal. Other phosphorus species such as particulate phosphorus, condensed polyphosphates, and colloids are removed by secondary mechanisms (adsorption, coagulation, sedimentation, and filtration) (Reddy et al., 1998).

2.2.2 Phosphorus removal by biological methods

Biological wastewater treatment is used to remove organic matter, but also for the removal of nutrients such as phosphorus and nitrogen. The basic processes in biological treatment is that microorganisms are given conditions for using the organic substance in the wastewater as a substrate (nutrient) (Morse et al., 1998). There is a wide variety of processes and reactor designs for biological treatment methods, but can mainly distinguish between aerobic and anaerobic processes.

Biological P removal began on 1960's and generally referred to as EBPR (Ødegaard et al., 2014). There are two main types of EBPR are P removal by maintaining attached growth in the system called biofilm and by maintaining suspended growth in the system called activated sludge.

2.3 EBPR Overview

Beyond the metabolic P requirements, the EBPR is a well-established technology for removing phosphorus from wastewater. The EBPR process is based on microorganisms with the ability to accumulate P from the wastewater for cellular growth, therefore removing P from the liquid phase. Referring to Mino et al. (1995), Polyphosphate Accumulating Organisms (PAOs) is responsible for EBPR phenomenon related to the removal of phosphorus in activated sludge systems, it was first noted in the late 1950s (Henze, 2008). Figure 2.3 show the basic configuration of the EBPR process in activated sludge where the bio-P sludge is returned to an anaerobic and subsequent aerobic phase after the separation step.
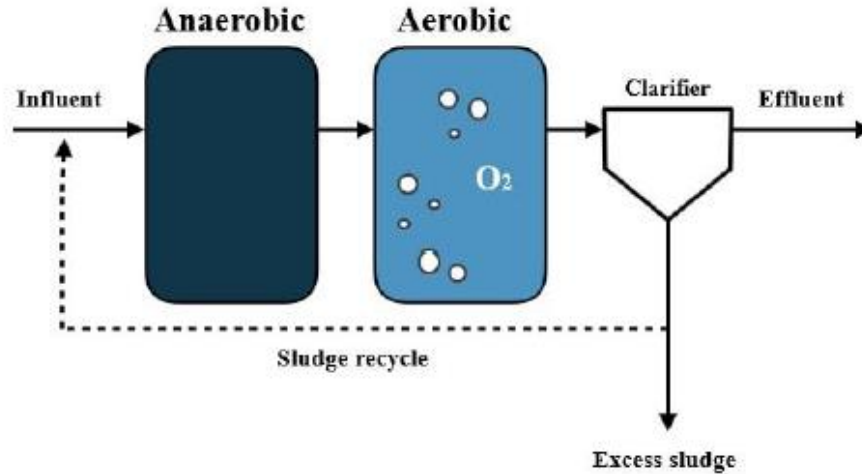
Figure 2.3: The principle of EBPR process configuration, modified from (Janssen et al., 2002)

EBPR can achieve P removal as long as the wastewater contains organic substrate in the form of VFAs (Ali et al., 2015). VFAs such as acetic, propionic and butyric acids are introduced into the anaerobic zone and used by the PAO for P removal (Leif Ydstebø, 2005).

2.3.1 Anaerobic zone

The anaerobic zone of EBPR is placed first in the bioreactor where the wastewater and the return activated sludge (RAS) are mixed (figure 2.3). The principal function of the anaerobic zone is to establish anaerobic conditions for fermentation of organic substrates to compounds such as ethanol, VFA, and succinate, that serves as carbon sources for PAO (Cloete & Muyima, 1997). The anaerobic zone act as a selector for PAOs capable of uptake and storage of excess P beyond ordinary cell requirements (Leif Ydstebø, 2005). Soluble P is released to the liquid phase. Figure 2.4 is a simplified illustration of biochemical processes under anaerobic and aerobic conditions.
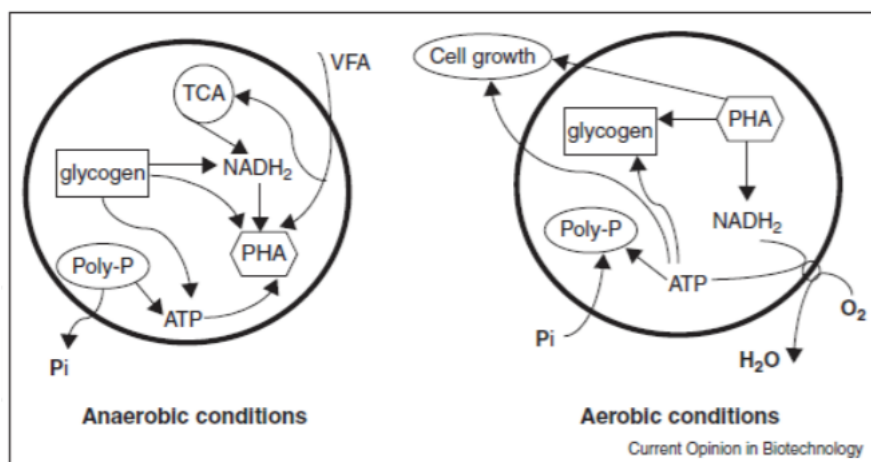
Figure 2.4: Schematic diagram of the PAO metabolism under anaerobic and aerobic conditions in the EBPR process (adopted from Lin, H et al., 2015).

The anaerobic detention time is the importance of the process. The anaerobic zone is provides the favourable conditions for the proliferation of PAOs and growth with a short HRT (Hydraulic Retention Time) between 0.5 and 1.0 hour (Sedlak, 1991). The biodegradable COD is fermented to VFA and consumed by the PAOs. They store it as intracellular Poly-Hydroxy-butyrate (PHB) storage products and release orthophosphates for energy purposes.

The anaerobic contact time for biological phosphorus removal systems has in most cases been arbitrarily selected between 1-2 hours. The detention time needed is to provide VFA for uptake by the phosphorus storing organisms and to allow sufficient fermentation. The EBPR performance is sensitive to changes in the anaerobic nominal HRT. It is also a function of the available substrate compared to available P ratio in the anaerobic zone.

2.3.2 Aerobic zone

The purpose of the aerobic zone is to metabolize PHB for new cell synthesis based on released energy from PHB oxidation. This energy is used to form polyphosphate in the cell and this incorporation into polyphosphate and leading to the removal of orthophosphates (Tchobanoglous et al., 2014). When the biomass is wasted phosphorus is removed from the system. The Specific aerobic growth rate maximum is $0.95\ d^{-1}$, as it was observed for PAOs by Barker and Dold (1997).

Principle of EBPR is the biological uptake and removal of phosphorus by activated sludge system in surplus of the amount that would be removed by completely aerobic activated sludge systems. In the completely aerobic activated sludge system typically the amount of P incorporated in the sludge mass is about 0.02 mg P/mg VSS (0.015 mg P/mg TSS) (Henze, 2008) which has been found to remove of 15 – 25 % of P in municipal wastewater (M. C. Wentzel et al., 2008). In EBPR activated sludge the incorporation of P in the biomass can increase to 0.06 – 0.15 mg P/mg VSS and give a higher P removal from the wastewater (M. C. Wentzel et al., 2008).

Figure 2.5 show an example of the experimental result from phosphate release in anaerobic conditions and uptake in aerobic conditions (Figure A). Figure A show a typical profile of extracellular P, PHA, Acetate, and glycogen as a selectively enriched PAO sludge (Saunders et al., 2003). Deterioration of P removal performance of laboratory scale EBPR reactors has been analysed and attributed spread of GAOs (Figure B) (Mino et al., 1995). GAOs have the ability to anaerobically uptake VFA, they use glycogen as their energy source as they do not store poly-P (Saunders et al., 2003).
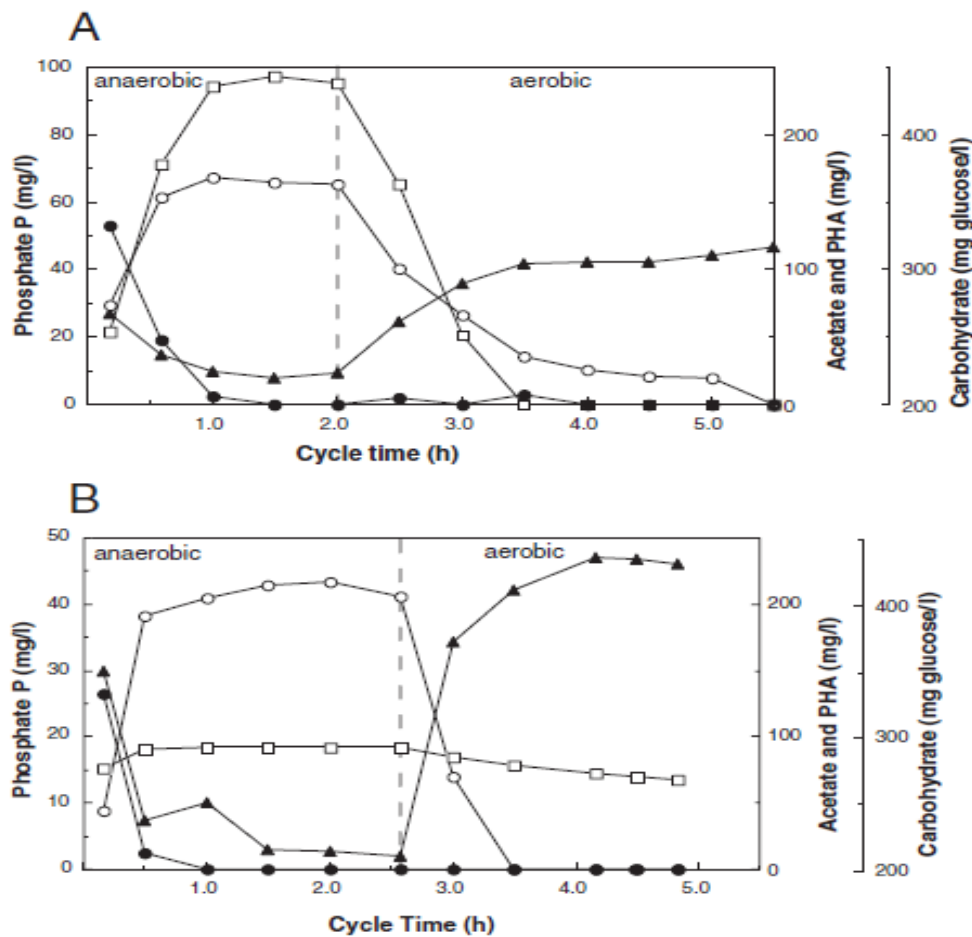
Figure 2.5: Profiles of extracellular phosphate-P (−■−), acetate (−●−), PHA (-o-), and glycogen (−▲−) during the anaerobic and aerobic reactor cycle stages of a typical PAO sludge (A) and GAO sludge (B) (adopted from Saunders et al., 2003).

2.3.3 Factors can affect the EBPR

EBPR is a well-known technology for removing phosphorus from wastewater. However, the processes remain operationally unstable in some systems, primarily because of a lack of understanding regarding the microbiology of EBPR. Many factors can affect the phosphorous removal efficiency which are related to wastewater characteristics, system design, and operational methods (Sedlak, 1991). Referring to Sedlak (1991), the following categories from these factors as below:

1. Environmental factors such as temperature, pH, and DO (Dissolved Oxygen).
2. Design parameters, such as system solid retention time (SRT), anaerobic zone detention time, aerobic zone detention time.
3. Availability substrate as affected by influent wastewater characteristics, carbon source, the level of VFA production.

Environmental Factors

Temperature

The Influence of temperature on EBPR is not always clear. Some studies have shown contradicting results about the effect temperature in the EBPR process. Decreases in temperature can have a negative effect because of the lower reaction rate of PAOs (Janssen et al., 2002).

Typical of Norwegian wastewaters is low winter temperature. Average temperature wastewater during winter can be 5°C, while during spring the temperature average of wastewater can be below 5°C due to snow melting (as a function of leakage water) (Ødegaard et al., 2014). Low temperature reduces the rate of biological reactions and reduces the rate of biological processes.

Some studies have shown that a lower temperature decreases the rates of biochemical transformations, such as P release/uptake, VFA uptake, PHA (Poly-hydroxy-alkanoate) oxidation, growth (Brdjanovic et al., 1998). Some studies have shown reduced efficiency of EBPR in high temperatures. Panswad, Doungchai, and Anotai (2003), observed at 20°C that PAOs were the main microorganisms in the EBPR system while the fraction of GAOs (Glycogen Accumulating Organisms) increased and became dominating as the temperature was elevated to 25°C and 30°C, hence decreasing the P removal in the system. At high temperatures, GAOs tend to consume substrate more efficient than PAOs (Oehmen et al., 2007), while they perform low or no phosphorus removal.

Other studies have shown that biological P removal will work better at temperatures 5-10°C (Erdal et al., 2003). This is because of the other bacteria present are more sensitive to low temperatures compared to PAOs which then will have a competitive advantage (Janssen et al., 2002).

At the first EBPR plant in Grimstad-Norway investigation showed that low temperature (below 7°C) had low effect in the process (L. Ydstebø, Bilstad, & Kommedal, 2000). The effect of temperature cannot be treated as an isolated or standard condition. From these studies, one can conclude that at the Norwegian wastewater temperatures, a stable and efficient EBPR process is possible.

pH

The competition between PAOs and GAOs are influenced by pH. Phosphorus removal performance by selecting PAOs over GAOs can be improved by increased pH. It has been suggested that an anaerobic pH lower than 7.25 is where GAOs are able to anaerobically take up VFA faster than PAOs, while above this pH PAOs take up VFA faster (Filipe, Daigger, & Grady, 2001).

Typical Norwegian wastewater has low alkalinity with pH around 7-8 (Ødegaard et al., 2014), also the topography gives the wastewater oxidizing and slightly alkaline conditions. Based on literature one, can assume that for the typical Norwegian wastewater pH will not be a problem for EBPR as it is within the range of optimal pH and will favour the growth of PAOs.

The DO concentration is one of the most important parameters for maintaining a healthy ecology in rivers and natural streams. If wastewater with high BOD is discharged into a stream, the DO in the water is used up by microorganism during degradation of BOD (organic matter). This could result in a drop in DO concentration of the stream (Oehmen et al., 2007). In EBPR plants, the competition between PAOs and GAOs is also affected by DO concentration, therefore impacting EBPR performance.

Oehmen et al. (2007) investigated plants were the DO concentration was adjusted in full-scale wastewater plants and associated changes in process performance was identified. The sludge was assessed using staining techniques and the abundance of PAOs and tetrad forming organisms (TFOs) was determined. It was found that poor P removal performance and high number of TFOs were more frequently observed at very high DO concentrations of 4.5 to 5.0 mg/l, while at the DO concentrations of approximately 2.5 to 3.0 mg/l seemed to relate with a greater abundance of PAOs (Y Comeau, Hall, Hancock, & Oldham, 1986). If a high DO sludge for example 5 mg/l is returned from aerobic to anaerobic zone it could be adversely affecting EBPR regardless of PAOs because of O_2 in the anaerobic zone.

Design Parameters

HRT & SRT

HRT and SRT are parameters can influence the EBPR performance. Brdjanovic et al. (1998) show in an experiment, that the increase of SRT could lead to the decrease of biomass yield and excess sludge discharge, which reduced the P removal regardless of PAO and GAO presence.

The phosphorus content in biomass increased but phosphorus removal efficiency did not change as SRT increased (Randall et al., 1992). It is clearly indicated that if the SRT-temperature combination is below a critical value EBPR ceases before other heterotrophic organisms. The main effect of system SRT in EBPR system is the PHA and glycogen polymerization reactions. Li et al. (2008) reported, reduced performance and worse settleability of the sludge when the SRT was increased from 8 to 16 days. At 8 days SRT it was achieved phosphate removal efficiency >90% and at 16 days SRT a decrease of phosphate removal to <85% was observed. But still there a lot of apparent contradiction about the effect of SRT on EBPR performance.

The efficiency of removal of P and N were raised with reducing HRT as the F/M (Food/Microorganism) loading ratio increased and the capacity of biological treatment was enhanced (Li et al., 2008). The VFA concentration will be affected if the HRT is too short to effectively ferment the Readily Biodegradable Chemical Oxygen Demand (RBCOD) in anaerobic conditions. Too long

HRT in anaerobic conditions will lead to depletion of VFA and RBCOD before the wastewater reaches the aerobic zone.

Substrate Availability

The biological phosphorus removal mechanisms involve the importance of having organic fermentation products available for the PAO. The bigger amount of VFA and propionate available in the anaerobic zone, the greater amount of phosphorus will be removed. A total BOD/P ratio in the range of 20-30 g/g can provide effluent soluble phosphorus concentration below 1 mg P/l with a relatively low SRT relatively (Sedlak, 1991).

VFAs in influent wastewater can optimize the EBPR process and the bacterial population capable for increased phosphorus removal, in response to increased VFA or P concentration. 0.40 g VSS/g VFA is a typical cell yield for *Acinetobacter* (Sedlak, 1991). *Acinetobacter* species are necessary microorganisms, which responsible for EBPR because they can accumulate polyphosphate as a sole carbon and energy source. Assuming a cell phosphorus content of 10 percent, per gram of VFA used will remove 0.04 g phosphorus (Sedlak, 1991). Work by M. Wentzel et al (1985), showed that 1 g of phosphorus can be removed with the addition of 8.9 g VFA.

Yves Comeau, Rabionwitz, Hall, and Oldham (1987) operated parallel biological phosphorus removal pilot plants. An increase of 1 gram phosphorus removal for every 6.4 gram VFA added was observed for the unit receiving the extra VFA. By the addition of VFA to one train, the effluent soluble phosphorus decreased from 2 mg P/l to 0.5 mg P/l. These results suggest that biological phosphorus storing organisms show enhanced phosphorus uptake by VFA addition in the range of 1 mg phosphorus for each 7 to 9 mg of VFA added.

COD/P ratio

Another crucial parameter for the design and operation of EBPR is the influent COD or BOD to total phosphorus ratio (influent COD:P or influent:P). There is a stoichiometric requirement of COD for the removal of each P. However, a system limited by COD or BOD or phosphorus determines the extent to which PAOs can grow, and the amount of excess phosphorus that can be taken up from the solution (Oehmen et al., 2007). The PAOs tend to dominate at COD:P ratios of 10-20 mg COD/mg P. GAOs tend to dominate at COD:P ratios bigger than 50 mg COD/mg P. Optimum COD:P ratio and properly control over the operating conditions are required to utilize the competition for substrate between PAOs and GAOs.

Stoichiometry estimate about 10 g of biodegradable, soluble COD (BSCOD) is required to remove 1 g P by the biological mechanism EBPR. This value is based on the following assumptions (Tchobanoglous et al., 2014) :

(1) 1.06 g VFA/g BSCOD is produced in the anaerobic zone

(2) Cell yield is 0.3 g VSS/g VFA

(3) Cell phosphorus content of PAOs is 0.3 g P/g VSS

Other cations in the biological system with biological phosphate removal such as Ca, K (Potassium) and Mg (Magnesium) must be available in sufficient quantities for efficient phosphorus removal. Municipal wastewater usually has cations in the quantities required.

Schönborn, Bauer, and Röske (2001) showed that the composition and cation concentration of the influent wastewater is an important factor in maintaining the stability of the EBPR process in the activated sludge. Because each phosphate molecule PO_4 contains 3 negative charges, it is unable to pass through the cell membrane on its own. The phosphate molecule must bond with positively charged ions such as Mg^{2+}, K^+ to pass through the cell membrane. If the phosphate molecule bonds with these charged ions it can become neutral and transported across the cell membrane. That is why Mg^{2+} and K^+ are essential cations for EBPR than just providing charge neutralization.

2.4   Settling Tanks

Settling is an important process in the unit operations in WWTP. The most important and commonly used of these unit processes are primary settling tanks (PSTs) and secondary settling tanks (SSTs) (Loosdrecht et al., 2016). PSTs is a treatment unit before the biological reactor. SSTs is a clarification step prior to discharge into receiving water.

Settling has an important role in new technologies because settling is applied in such as new granular sludge reactors. Raw wastewater secondary settling settles as flocculent settling, and activated sludge follows hindered settling and granules settle with discrete settling.

2.4.1 Primary Settling Tanks

Improved PST models are an important part of the whole WWTP since their impact on wastewater fractionation may be significant. Phillips et al. (2009), Henze et al. (2000) and Choubert et al. (2013) have shown that sludge production is influenced by the estimated inert particulate COD.

A high content of RBCOD, especially VFA in the influent WWTP needed to promote EBPR in activated sludge process cycles (Pitman et al., 1992). If the wastewater influent contains a low concentration of VFA, it can be increased by external substrate addition or produced by WWTP itself by fermenting the primary sludge (Ribes et al., 2002).

Fermentation in PSTs is one way to produced substrates. Fermentation in PST determines the amount of phosphorus that can be removed per unit of VFA generated in or added to anaerobic zone. The amount of BOD that can be converted to VFA, can predict the phosphorus removal capacity in wastewater treatment (Sedlak, 1991).

Experiments by Ubay-Cokgor et al. (2005) show that fermentation converted between 18 – 30 % of the initial VSS in the sludge to biodegradable COD. The average VFA composition in fermentation was 50% acetic acid (HAc), 33% propionic acid, 9% butyric acid and 8% valeric acid (Ubay-Cokgor et al., 2005). This indicate that the most important VFA is as carbon sources for nutrient removal in biological processes.

2.4.2 Secondary Settling Tanks

One crucial design factor to achieve successful operation of an EBPR is a design of the SST. The SST should provide effective clarification of the sludge because the biomass suspended solids contain phosphorus and must be removed to a low level to meet the effluent requirement.

The most common sludge separation method in active sludge plants is sedimentation. Because the resolubilizing of phosphorus in the sludge blanket can be a problem, it can be reduced by increasing the side water depth or increase return sludge pumping rate (Reddy et al., 1998). Normally, a settling tank with a relatively large depth of more 4m is used, so that a horizontal/vertical flow in the settling tank is obtained and there is a large storage volume for sludge (Ødegaard et al., 2014). In activated sludge is important to know MLSS (Mixed Liquor Suspended Solid) concentration, SVI and return sludge.

According to Ødegaard et al. (2014), the function of the settling tank is critical at peak loads since the sludge then tumbles into the tank. If the concentration (thickening) is not good enough and the sludge storage volume is not large enough, the sludge level in the tank will rise and eventually follow the water out. Not only is the cleaning result then poor, but the very basis of the process (the activated sludge) can be lost - in whole or in part. In the case of the active sludge process, the sludge separation is therefore of particular importance, since the sludge from the separation step is returned to the aeration tank.
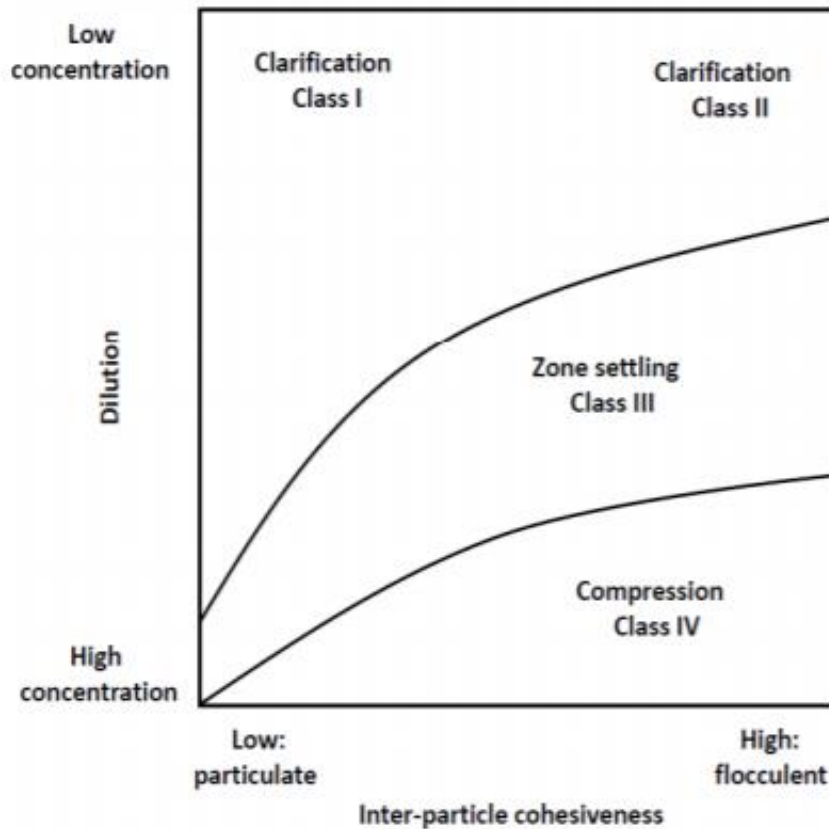
Figure 2.6: settling regimes (adopted from Ekama et al., 1997)

Settling behaviour of activated sludge is dependent on the concentration of the suspended solids and flocculation behaviour. Figure 2.6 show different settling regimes that can be distinguished as Class I, Class II, Class III and Class IV (Ekama et al., 1997). Which is:

• Class I: Discrete non-flocculent settling or discrete settling

• Class II: Discrete flocculent settling or flocculent settling

• Class III: Zone settling or hindered settling

• Class IV: Compression settling

In activated sludge, if the total suspended solid (TSS) concentrations are below 600 – 700 mg/l (dependent on the settleability of sludge), the particles are disbanded so there is no physical contact between the particles and the particles are too far apart to sense each other (Egala et al., 2012). On this condition, particles have a low tendency to flocculate. Each particle will settle at its own characteristic velocity. This regime is called discrete settling (Class I). Class II (regime of flocculent settling) is when the particles do have a tendency to flocculate, they will form larger flocs over time but still settle as individual flocs. These two regimes are also called a clarification regime because they both occur in the clarification zone (Egala et al., 2012).

According to Ekama et al. (1997) and Egala et al. (2012), if the TSS concentration is above 600 – 700 mg/l, the settling regime become the hindered settling regime (Class III). In this condition, the distance between the particles are much smaller, but still, there is no physical contact between them. In this regime, a discrete interface between the clear supernatant and the subsiding flocs can be observed. This interface is called a sludge blanket.

When the TSS concentration increase above 3000 – 7000 mg/l which depend on the settleability of the sludge (De Clercq et al., 2008). The distance between the particles becomes so small that the settling behaviour of the particles are influenced by the actual physical contact between the flocs (De Clercq et al., 2008). This is called compression settling (Class IV).

Adapted from Wisconsin Department of Natural Resources (January 2009 Edition), figure 2.7 describe and show typical EBPR reactor and the settling tank configuration.
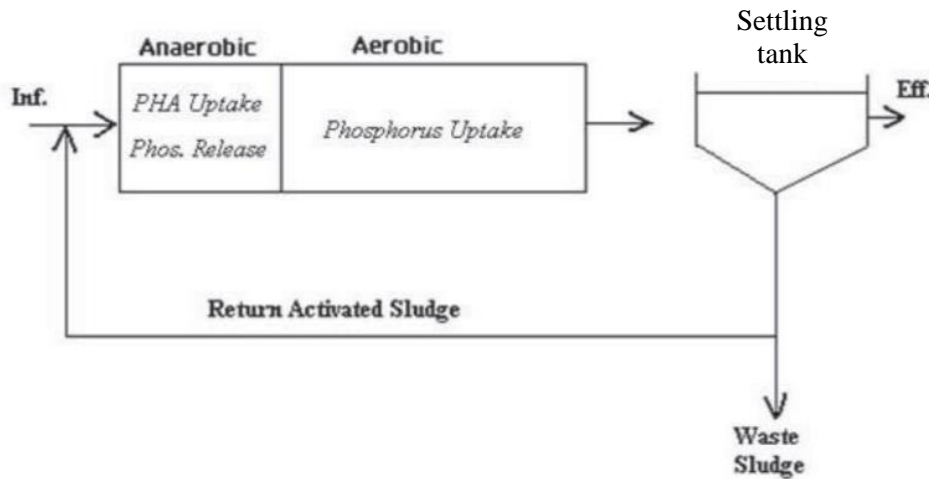
Figure 2.7: Show typical EBPR reactor configuration. (Adapted from Wisconsin Department of Natural Resources, January 2009 Edition).
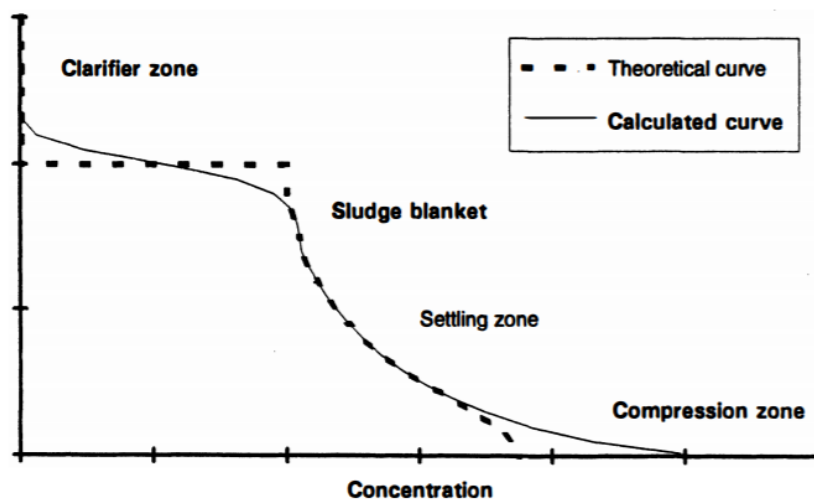
Figure 2.8: Expected and calculated sludge profile in the clarifier (Adopted from Dupont and Henze, 1992)

Figure 2.8 show the sludge concentration profile for SST under steady state conditions. There are two curves, one is the theoretical curve and the other is based on calculation with the model. The calculated curve starts with a sludge concentration almost zero at the top of clarifier, and the concentration increase as one move down in the sludge blanket (Dupont & Henze, 1992).

Temperature and solids concentration also affect the settling performance. As Stokes law state, the setting velocity of particles depend on viscosity. Biological activity and most chemical reactions are slowed down at lower temperatures (Laikari, 1988). Increase of solids concentration will reduce the influence of temperature on the functions of the settling tank and sludge blanket. Furthermore, the decrease of temperature will reduce the sludge flocculation by decreased production of biopolymers and consequently reduce the settling performance of the sludge (Laikari, 1988).

2.5   Overview of SNJ WWTP

SNJ is the largest and most advanced WWTP in the Rogaland region. It is located in Mekjarvik in Randaberg municipality. The plant receives wastewater from the municipalities of Randaberg, Stavanger, Sola, Sandnes, and Gjesdal (Ivar, 2018). The plant was put in operation in 1992 as a chemical wastewater treatment and designed for 240 000 person equivalents (pe). Because of more strict discharge limits and population growth in the region, the plant has been expanded and rebuilt to biological treatment based on biological phosphorus removal. Today's load to SNJ is approx. 300,000 pe (average, 2014). The forecasts show strong population growth in the region in the coming years. The new plant is designed for 400,000 pe (step 1, 2035) and 500,000 pe (step 2, 2050) (Ivar, 2018).

The biological plant is divided into 3 process lines, each consisting of 1 bioreactor and 4 settling tanks. The bioreactors contain 3 anaerobic tanks and 1 aerobic tank. During summer 2017 the biological treatment at SNJ was started.

2.6 Aim

The aim of this master thesis was to study and investigate the performance of the EBPR process in SNJ. The main tasks to be performed were:
- Characterization of the wastewater by determining the daily/weekly variation of parameters relevant to EBPR implementation.
- Investigate of phosphorus release and uptake both in the full-scale plant and in batch experiments at the laboratory.
- Evaluate the performance of the plant

2.7 Outline of the work

- The thesis is based on theoretical studies and practical work at the plant.
- The practical work was carried out during three months from January to March 2019
- Operational parameters were recorded during the experimental period, such as incoming flow, return sludge flow, oxygen levels and sludge blanket height in the settling tanks.

3. Materials and Methods

This section describes the materials and methods used for the experiments and tests performed during the experimental work of the master thesis. The methods and experiments performed are divided into 3 subsections. All laboratory work for this master thesis project was conducted at the process laboratory at SNJ.

3.1 Sampling techniques

All samples used in this research was collected as grab samples from SNJ WWTP biological line 1. Samples were collected in plastic bottles from the bioreactor line. The first sample taken from the inlet of the biological treatment, then from the settling tanks (1, 2, 3, 4), aerobic tank (Aer 1 (inlet aerobic tank), Aer 2 (outlet aerobic tank)) and anaerobic zones (An 1, An 2, An 3), then immediately brought the samples to the process laboratory for separation and analysis. Samples were collected from the aerobic zone first and finally from the anaerobic, so anaerobic samples had the shortest times plan between sampling, filtration, and analysis or conservation (Egeland, 2018). The temperature, pH, conductivity and DO were measured before the samples were collected. For measurements of temperature, pH, conductivity, and DO a portable WTW Multi 3630 IDS pH/Conductivity/O_2 was used.

All samples taken from line 1 were immediately brought to the laboratory for further analysis (see on part 3.3). A thermo Scientific Megafuge 8 centrifuge was used for solid–liquid separation and the filtered samples were added 4M H_2SO_4 for preservation and analysed later. Filtered samples were used to analyses PO_4-P and filtered COD.

3.2 Experimental Procedures

3.2.1 Primary Sludge Fermentation

Primary sludge was collected from the filter unit and concentrated to achieve approximately 1-1.5 % TS (Total Solid). A laboratory scale fermentor has been used to study the primary sludge fermentation for production of VFA as the substrate for the next tests (see section 3.2.2).
The primary sludge samples were homogenized and transferred to an Erlenmeyer flask and placed on a magnetic stirrer. The section following 3 steps:
1. Primary sludge fermentation
   The fermentation reactor was made from Erlenmeyer flask of 500 ml volume and stirred at 100-200 rpm for 2-3 days. Before the fermentation started, pH, temperature, conductivity,

DO, TS, filtered COD, and PO$_4$-P were measured.

2. After 2-3 days of fermentation, samples taken for measured pH, VFA, alkalinity, PO$_4$-P, NH$_4$-N, and filtered COD

3. The filtrate of fermented primary sludge was used for the analysis of anaerobic P release and P release/uptake test in laboratory (section 3.2.2)

Overview of the experimental conditions from primary sludge fermentation shown in table 3.1.

Table 3.1: Experimental conditions of the primary fermentation tests

Test No.	Date	Duration (day)	Initial experimental condition						
			DO (mg/l)	Conductivity (mS/cm)	pH	Temp (°C)	TS (%)	PO$_4$-P (mg/l)	COD$_{filt}$ (mg/l)
0	22.01.2019	3	0.54	2.58	6.88	12.2	0.80	n.a	n.a
1	29.01.2019	2	0.35	3.24	7.60	13.5	0.92	3.3	114
2	04.02.2019	3	n.a	n.a	7.72	11.5	1.49	3.8	n.a
3	12.02.2019	2	n.a	3.20	6.57	12.1	1.57	39.6	576
4	18.02.2019	2	n.a	3.20	6.79	n.a	1.20	28.6	118
5	25.02.2019	2	n.a	3.00	6.91	n.a	1.30	n.a	n.a
6	04.03.2019	2	n.a	6.82	7.28	10.2	1.38	n.a	n.a

Test 0 was used for fermentation test, for analysis VFA concentration, alkalinity, and pH. Test 1-3 were used for anaerobic P release test. Test 4-6 were used for analysis P release and uptake in laboratory batch experiment. Test 1-3 and 4-6 will be defined on section 3.2.2.

3.2.2 Anaerobe Phosphate Release Test in the Lab Bioreactor & Lab Batch Test

Anaerobic Phosphate Release Test in the Laboratory Bioreactor

Activated sludge was collected from the L1 bioreactor effluent. Phosphate release tests were done with sludge to observe the actual condition in the bioreactor. Samples collected from bioreactor effluent were immediately carried to the laboratory for centrifugation and filtration prior to conservation. Samples from the bioreactor were immediately moved into Erlenmeyer flask of 250 ml and placed on a magnetic stirrer. Some Styrofoam beads were put on the surface to minimize gas exchange through the air-water interface to maintain anaerobic conditions. Samples for analysis were taken each hour. Filtered samples were collected and added 4M H$_2$SO$_4$ for preservation and later analysed.

Table 3.2: The experimental conditions of the tests.

Test No.	Date	VFA addition (ml)	Initial experimental condition				
			DO (mg/l)	Conductivity (mS/cm)	pH	Temp (°C)	TSS (mg/l)
1	31.01.2019	0,30,70	n.a	n.a	7.13	13.5	1960*
2	07.02.2019	0, 50, 100	1.03	n.a	6.82	11.0	2166*
3	14.02.2019	0, 30, 50	0.43	2.50	7.64	10.3	914*

*TSS unconcentrated

Test 1,2, and 3 were done with variable addition of VFA, ranging from 0 which correspond to endogenous P release and to various VFA levels up to 100 ml, shown in table 3.2. Samples were taken hourly for analysis of PO_4-P, VFA, alkalinity, and filtrated COD.

Phosphate Release and Uptake Test in Laboratory

Activated sludge was collected from L1 bioreactor effluent. The tests were done on concentrated and unconcentrated sludge. Sludges were concentrated to achieve higher reaction rates during the test. Samples were collected and settled until wanted concentration was reached. Samples from the bioreactor were immediately moved into Erlenmeyer flask of 250 ml and placed on a magnetic stirrer. Some Styrofoam beads were put on the surface to minimize gas exchange through the air-water interface to maintain anaerobic conditions. The samples were centrifuged and filtered prior to conservation.

Table 3.3: The experimental conditions of laboratory batch tests.

Test No.	Date	VFA addition (ml)	Initial experimental condition				
			DO (mg/l)	Conductivity (mS/cm)	pH	Temp (°C)	TSS (mg/l)
4	20.02.2019	0,30,50	n.a	4.23	6.98	n.a	2229/4872**
5	27.02.2019	0, 30, 50	n.a	n.a	6.01	n.a	1330*
6	06.03.2019	0, 30, 50	n.a	5.64	7.01	n.a	1362*

**TSS unconcentrated/concentrated; *TSS unconcentrated

These experiments to review phosphorus release and uptake were investigated under anaerobic and aerobic conditions respectively. Tests 4-6 were performed to study the relationship between phosphorus release reaction and uptake of VFA organic substrates at three concentrations of

VFA volume added (0, 30 and 50 ml) in the anaerobic step of biological phosphorus removal.

To measure the P release and uptake in the system a mini-reactor was made in the laboratory. This process has first anaerobic conditions and then continue with aerobic conditions. The first 3-4 hours was anaerobic process and after 3-4 hours the reactor was aerobic. Samples for analysis were taken each hour. Test was done at three different VFA additions volume. Filtered samples were collected and added 4M H_2SO_4 for preservation and later analysed.

3.2.4 Sludge Blanket Level in The Settling Tank

During the experiment, the level of sludge blanket in the settling tanks from line 1 (Settling tank 1, 2, 3 and 4) was measured. Settling tanks sludge blanket level was usually measured at 12-14 pm, 1-2 times a week using a portable SS Partech 740. The sludge blanket level indicates accumulation of sludge in the settling tank, and how long the sludge remains there. If it stays for too long it becomes anaerobic and releases PO_4^- which go to effluent. Higher PO_4^- in the effluent reduces P removal efficiency.

3.3 Analytical Procedures

3.3.1 Temperature, pH, Conductivity, DO

A portable WTW Multi 3630 IDS pH/Conductivity/O_2 meter was used for determination of temperature, pH, conductivity and DO. Measurements were done directly in the biological process line 1 at SNJ. The overview of probes used and calibration intervals are shown in table 3.4

Table 3.4: Overview of portable WTW Multi 3630 IDS pH/conductivity/O_2 meter.

Analysis	Probe used	Calibration interval
pH	WTW pH-Electrode Sentix 940	Weekly with pH 4 and 7 buffer solutions
Conductivity	WTW Tetracon 925	Weekly with a standard KCl solution
DO	WTW FDO 925	Calibrated prior to each use

3.3.2 Solid analysis

TSS was determined by filtrating samples through a 47 mm diameter filter Whatman GF/C with 1 μm pores and drying in a Fermaks TS9053 drying oven at 105 °C in minimum 2 hours and maximal 14-16 hours (IVAR regulation). VSS was determined from TSS samples after combustion at 550 °C for 20 – 30 minutes in a Carbolite Furnaces CSF 1100 muffle oven. The sample was cooled

in the desiccator and then weighed on a Satorius Basic B 120 S scale for determination of the TSS and VSS in mg/l.

TS was determined by drying a known amount of sample in an aluminium dish overnight. TVS (Total Volatile Solid) was determined by combustion the TS sample at 550 °C for 20-30 minutes in the muffle oven.

Solid analysis procedures were according to IVAR internal procedures and standardized methods for wastewater analysis is by Clesceri, Greenberg, and Eaton (1998).

3.3.3 Total VFA and Alkalinity Measurement

According to Moosbrugger, Wentzel, Ekama, and Marais (1993), VFA and alkalinity were determined by a 5 points pH acid titration method. The 5 points titrations with Hydrochloric acid (HCl 0,05 M) was done to pH 6.7 ± 0.1, 5.9 ± 0.1, 5.2 ± 0.1, and 4.3 ± 0.1. If the sample pH was lower than 6.6, it was adjusted to 6.7 ± 0.1 with NaOH (0,05 M). The samples were centrifuged and/or filtered and if necessary diluted with distilled water and total sample volume 50 ml. The sample used for titration was then placed on a magnetic stirrer for mixing at a low rotation speed. The initial pH of the sample and volume HCl consumed to each pH point was recorded. The data from the titration was entered into the computer program TITRA 5. This software calculated the total VFA concentration expressed as mg HAc/l and alkalinity as mg/l $CaCO_3$.

3.3.4 PO_4-P, NH_4-N, and filtered COD

All the analyses were performed by following IVAR internal procedures, which are in compliance with Norwegian standards for wastewater analyses. The following analyses were done at the Spectrophotometer with Spectroquant Prove 300.

PO_4-P Analysis

PO_4-P was determined by adding 10 ml of prepared wastewater sample (diluted or undiluted) into an empty Spectroquant 16 mm test cell. Molybdate and ascorbic reagents were added each at 400 µL to the samples and mixed. After 10 minutes the samples were analysed with a Spectroquant Prove 300 spectrophotometer. The spectrophotometer was zero adjusted by Merck Spectroquant Zero Cell prior to each analysis series.

NH$_4$-N Analysis

NH$_4$-N was analysed using a Merck Spectroquant Ammonium Cell Test with a range of 4.0 – 80.0 mg/l NH$_4$-N. 0.1 ml filtered sample (diluted or undiluted) was added to the alkaline test cell, and then added one dose of the enclosed NH$_4$-K reagent. The samples were mixed and wait for 15 minutes before analysed with the Spectrophotometer Prove 300.

Filtered COD

Filtered COD were analysed with the Spectrophotometer Prove 300. Filtered COD was analysed using Merck Spectroquant COD cell test kit with range 10 – 150 mg/l COD for the wastewater and kit with range 25 – 1500 mg/l COD were used for analysed samples from primary sludge fermentation. The procedures of filtered COD measurements were digesting 3 ml of filtered sample (diluted or undiluted) in Spectroquant TR420 Thermoreactor at 148 °C for 2 hours. After digestion, cooling the samples for 10 minutes in the tube rack and then mixed before cooling to room temperature. Samples with kit range 10 – 150 mg/l cells were read at wavelength 445 nm. For samples with range 25 – 1500 mg/l were determined at 605 nm wavelength.

4. Results

All result obtained experimental works are presented and discussed in this chapter. This chapter divided into six sections: *(1) Rogaland wastewater variations and characteristics; (2) Primary sludge fermentation and anaerobe phosphate release test; (3) Overview phosphate release in the bioreactor and batch test; (4) Sludge blanket level in settling tanks; (5) Mass balance in the bioreactor and (6) Limitations and error analysis*. The presented data and figures are given in this chapter, while the collected raw data are presented in the Appendixes.

4.1 Rogaland wastewater variations and characteristics

It is important to know the characteristics and variations of wastewater to evaluate the design and performance of the EBPR system. Concentrations of substances in wastewater varies from time to time. The analyses in this thesis are during January – March 2019, wastewater was characterized to evaluate the composition, trends, deviations, and condition in relation to the wastewater compounds.

Flowrate & HRT

The recorded average daily influent flow variation from line 1 during the period January 17th until March 7th, 2019 are shown on figure 4.1. Data from table 4.1 was used as input flow for analyses. The average flow data on each sampling was obtained from SNJ WWTP's digital process control system AIM.

Table 4.1: The flow in the SNJ during January – March 2019

Date	Flow rate (m³/d)
17.01.2019	114,019
22.01.2019	107,477
29.01.2019	81,224
04.02.2019	114, 254
12.02.2019	98,394
19.02.2019	83,143
26.02.2019	68,615
28.02.2019	72,483
04.03.2019	104,527
07.03.2019	110,604
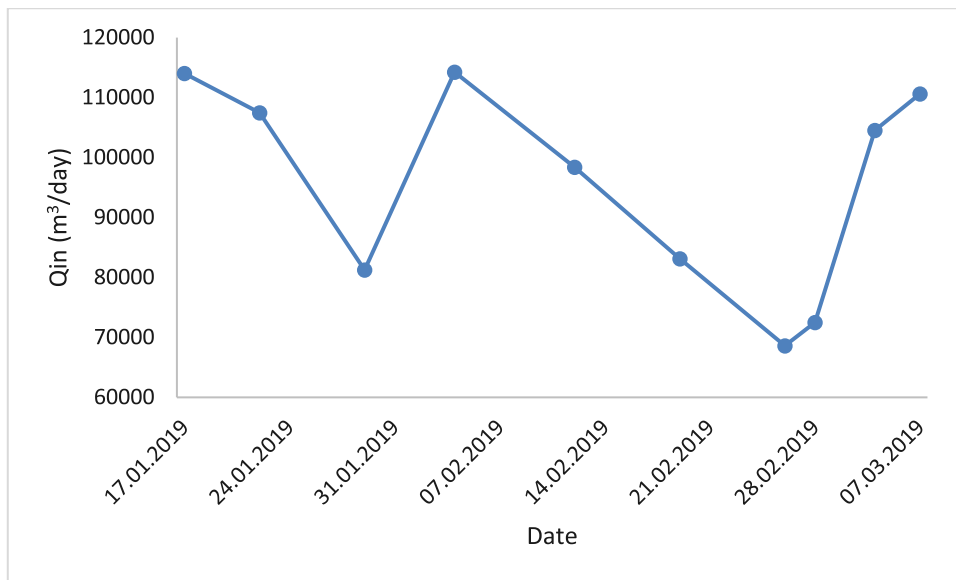
Figure 4.1: Influent flow (Qin) during period 17 January – 7 March 2019

Figure 4.1, show the influent changes from time to time. The flow on Jan 17th, Feb 4th, and March 7th are the highest flow during period January - March. It was because of the influence of rain during the sampling, and there were also unstable operational conditions in the treatment plant in March. As the biological treatment plant is still quite new, they have been working with some testing, and in March they start with new filter washing procedure. This would also have an effect on the results of the sampling campaigns. Lower influent flow will normally be associated with more concentrated wastewater compared to higher influent flow caused by rain and dilution of the wastewater.

Table 4.2, 4.3 and 4.4 show the flow, DO, conductivity, pH, temperature, TSS, PO_4-P, COD filtered and C:P from SNJ WWTP's Line 1. Table 4.2 is when the flow is at the lowest condition, table 4.3 show when the flow is at the average condition, and table 4.4 when the flow is at the highest condition when the samples were collected.

Table 4.2: Condition at minimum flowrate

Position	Q (m³/h)	DO (mg/l)	Conductivity (mS/cm)	pH	Temp. (°C)	TSS (mg/l)	PO₄-P (mg/l)	CODfilt (mg/l)	C/P (mg/l)
Inlet L1	1440	1.42	3.82	7.52	12.6	208	1.59	45	28.30
An 1 (RAS)	800*	0.39	3.26	7.22	11.8	5185	3.26	24	7.36
An 2	2240**	0.38	4.83	7.22	11.5	1471	2.58	150	58.14
An 3	2240	0.45	3.85	7.20	12.3	1680	1.76	80	45.45
Aer 1	2240	0.46	3.45	7.50	11.8	1852	0.94	22	23.40
Aer 2	2240	0.42	3.28	7.65	12.5	1960	1.02	20	19.61
Effluent	2240	6.10	3.07	7.45	13.4	31	1.44	19	13.19

Data from analysis on January, 29th 2019. Table show the condition at minimum flowrate.
(*: RAS ; **: RAS + inlet).

Table 4.3: Condition at average flowrate

Position	Q (m³/h)	DO (mg/l)	Conductivity (mS/cm)	pH	Temp. (°C)	TSS (mg/l)	PO₄-P (mg/l)	CODfilt (mg/l)	C/P (mg/l)
Inlet L1	2682	1.4	2.56	7.18	12.6	192.2	1.49	41	27.52
An 1 (RAS)	1050*	0.38	2.42	6.40	11.3	2300	2.52	26	10.32
An 2	3732**	0.34	2.60	6.57	11.6	956	1.90	68	35.79
An 3	3732	0.25	2.45	6.66	11.1	902	2.02	75	37.13
Aer 1	3732	1.42	2.47	6.82	11.5	1030	1.20	25	20.83
Aer 2	3732	1.64	2.52	6.93	11.3	947.5	0.74	38	51.35
Effluent	3732	n.a	2.76	6.99	13.43	30	1.32	27	20.45

Data from analysis on January, 22th 2019. Table show the condition at average flowrate.
(*: RAS ; **: RAS + inlet).

Table 4.4: Condition at high flowrate

Position	Q (m³/h)	DO (mg/l)	Conductivity (mS/cm)	pH	Temp. (°C)	TSS (mg/l)	PO₄-P (mg/l)	CODfilt (mg/l)	C/P (mg/l)
Inlet L1	3150	4.15	4.05	6.74	8.9	86.46	1.0	42	42
An 1 (RAS)	600*	0.21	4.31	6.96	9.2	2412.77	2.9	55	18.97
An 2	3750**	0.52	4.38	6.96	9.0	1057.14	1.6	31	19.38
An 3	3750	0.83	4.56	6.98	9.0	1509.68	1.8	38	21.11
Aer 1	3750	1.55	4.55	7.17	9.1	1197.30	0.9	34	37.78
Aer 2	3750	1.62	4.55	7.23	9.1	1248.49	0.8	33	41.25
Effluent	3750	n.a	3.73	7.40	9.1	17.97	1.25	35	28

Data from analysis on March, 11ᵗʰ 2019. Table show the condition when high flowrate.
(*: RAS ; **: RAS + inlet).

Not all data in table 4.2 - 4.4 were as expected. The DO in An 2 was probably caused by DO in influent wastewater, the influent came directly to An 2. However, the TSS measured in An1 was 20 – 30 % higher, this is because flow to An1 is from RAS and has a higher SS. TSS measured in An 2 and An 3 should also be similar and lower than An 1 because of dilution from inlet. TSS inlet in table 4.4 show lowest concentration compare to TSS inlet in table 4.2 and 4.3, because of high flowrate and diluted wastewater because of rain.

All results from daily analyses of Rogaland's wastewater from SNJ WWTP line 1 presented in appendix B.

Table 4.5: The HRT calculated during January – March from anaerobic and aerobic zones of L1 bioreactor.

Date	Unit	An 1	An 2	An 3	Aer 1	Aer 2	Total
	Volume* (m³)	550	940	940	2790	2790	8010
22.01.19	hour	0.52	0.25	0.25	0.75	0.75	2.52
29.01.19	hour	0.69	0.42	0.42	1.25	1.25	4.03
04.02.19	hour	0.46	0.25	0.25	0.73	0.73	2.42
19.02.19	hour	0.69	0.38	0.38	1.14	1.14	3.73
04.03.19	hour	0.99	0.30	0.30	0.88	0.88	3.35
11.03.19	hour	0.92	0.25	0.25	0.74	0.74	2.90

*Volume of bioreactor each condition, adapted from IVAR SNJ's book

HRT is calculated based on the total flow rates and reactor volume of the different zones. Exception for An 1 which was calculated based on the flow of RAS. HRT of An 2 and An 3 are equal,

as well as Aer 1 and Aer 2 because the volume is same and receives the same flow. An anaerobic HRT between 0.25 – 1 hour is within the recommended target (J. Barnard et al., (1984); J. Barnard (1998); C. L. Grady Jr, et al., (2011)). Longer anaerobic HRT tested laboratory-scale EBPR reactors ranging from 1.75 to 3 hours observed no apparent process problem (Coats, E. R. et al., 2011). But their research was principally focused on investigating the effects of nitrate on EBPR. HRT from this thesis in the anaerobic zone is between 0.25 – 0.99 hour and in aerobic zone are between 0.74 – 1.25 hour. This HRT indicate the favourable conditions for PAOs to proliferation and growth in the anaerobic reactor.

Temperature & pH

As mentioned in section 2.3.3, temperatures between 5 – 10°C are optimal for biological P removal. However, from the tables 4.2 – 4.4 the temperature was between 8 – 12 °C and during this study the temperature had no big effect on the process. Some measurement had high temperature because the measurement was not directly at the line, but measured in the laboratory.

Also, from section 2.3.3, the typical Norwegian wastewater has low alkalinity with pH around 7-8 (Ødegaard et al., 2014). This pH will affect the microbial mechanisms under anaerobic and aerobic conditions, and this affect to microbial competition between GAOs and PAOs. From table 4.2 – 4.4 pH in the biological process was 6.4 – 7.6 which indicated a condition with a good potential for removal of P. This is because PAOs will take up VFA faster than GAOs.

C/P

With reference to Oehmen et al. (2007), C/P ratio in the inlet should be lower than 50 mg/mg to favour PAOs growth over GAOs. As Gu et al. (2008) analysed, a C/P ratio of < 13 led to PAO dominance, a C/P > 50 led to GAO dominance and C/P ratio in between means this values led to coexistence of both PAOs and GAOs (Ahn et al., 2006); (Liu et al., 1997); (Schuler et al., 2003). However, observed a ratio of C/P between 5 and 38 predicting that plants contained a combination of PAOs and GAOs populations (Oehmen et al., 2007).

The range C/P average from SNJs is between 17 – 33 mg/mg, this mean the EBPR process with both PAOs and GAOs can coexist and maintain good and stable performance, as long as the condition is favourable for PAOs to preferably uptake of sufficient organic carbon to remove all the influent phosphorus.

F/M, MLSS, MLVSS

Table 4.6: Average operating conditions in the bioreactor during January – March 2019

Qin (m³/h)	MLSS (mg/l)	MLVSS (mg/l)	SVI (ml/g)	Q$_{RAS}$ (m³/h)	F/M – ratio (g COD/g MLSS.d^{-1})
2300	1350	1120	90	800	0.40

From table 4.6 the average F/M ratio at SNJ is 0.40 g COD/g MLSS.d^{-1}. Tchobanoglous et al. (2014), refers a ratio of F/M ranges between 0.05 to 0.3 g BOD/g MLSS.d^{-1}, and with a COD/BOD ratio of 2.15 (Ødegaard et al., 2014), the F/M ratio at SNJ is about 0.2 g BOD/g MLSS.d^{-1} and within reported values. The F/M ratio represents the amount of substrate that a given amount of biomass has available. From this, the result show F/M ratio that is acceptable for the municipal facility design.

Data from SNJ

Table 4.7 will show the data from SNJ during period January – April 2019. This calculation based on average data from 24 hours composite samples taken once a week.

Table 4.7: Measurement from SNJ during January – April 2019:

	Inlet	Outlet
Total P (mg/l)	4.5	2.48
PO$_4$-P (mg/l)	2.1	1.95
TS (mg/l)	236	25
VSS/TSS (mg/mg)	0.87	0.77
COD/TS (mg/mg)	1.23	1.25
COD/VSS (mg/mg)	1.41	1.62
PO$_4$-P/TS (mg/mg)	0.010	0.021
PO$_4$-P/VSS (mg/mg)	0.012	0.028

Calculation from table 4.7 show the result as below:

PO$_4$-P in VSS (g P/g VSS)	0.028
PO$_4$-P in OHO-VSS (g P/g VSS)	0.02
PO$_4$-P in PAO-VSS (g P/g VSS)	0.2
Total VSS (mg/l)	1000
PAO share (%)	4.5

Conclusion of average calculation from table 4.7 show as below:

P in SNJ (kg/d)	
Inlet	391.50
Outlet	215.76
Removal	175.74

Based on this, P removal efficiency in SNJ during period January – April is 44.9 %.

4.2 Primary Sludge Fermentation & Anaerobe Phosphate Release Test

Primary Sludge Fermentation Test

This section will present the results of fermentation from primary sludge. Primary sludge is an interesting way of improving nutrient removal because of readily biodegradable substrate can be produced directly on the wastewater treatment plants. In this study, primary sludge was taken and fermented over 2-3 days. However, longer fermentation periods are not efficient because it has no influence on the VFA composition and conversion of VFA to methane may reduce the VFA yield (Munch et al., 1996). Biodegradable carbon substrates can be produced on the WWTP itself by fermenting the primary sludge. VFAs are mainly products in the fermentation (Munch et al., 1996).

Test 0 is for fermentation test; pH, DO, VFA, filtered COD, alkalinity, and PO$_4$-P were measured. Table 4.8 is the result from test 0.

Table 4.8: VFA concentration, CaCO$_3$ as alkalinity, PO$_4$-P, filtered COD, NH$_4$-N and pH during fermentation test 0.

Time (hour)	pH	COD$_{filt}$ (mg/l)	NH$_4$-N (mg/l)	PO$_4$-P (mg/l)	DO (mg/l)	CaCO$_3$ (mg/l)	VFA (mg/l)
0	6.88	n.a	19.9	n.a	0.54	202.6	0
19	6.21	210	26.7	13.5	0.45	162.1	197.4
43	6.33	81	31.1	14.2	0.43	154.8	203.6
67	6.56	383	32.4	52.3	0.42	154.4	384.3
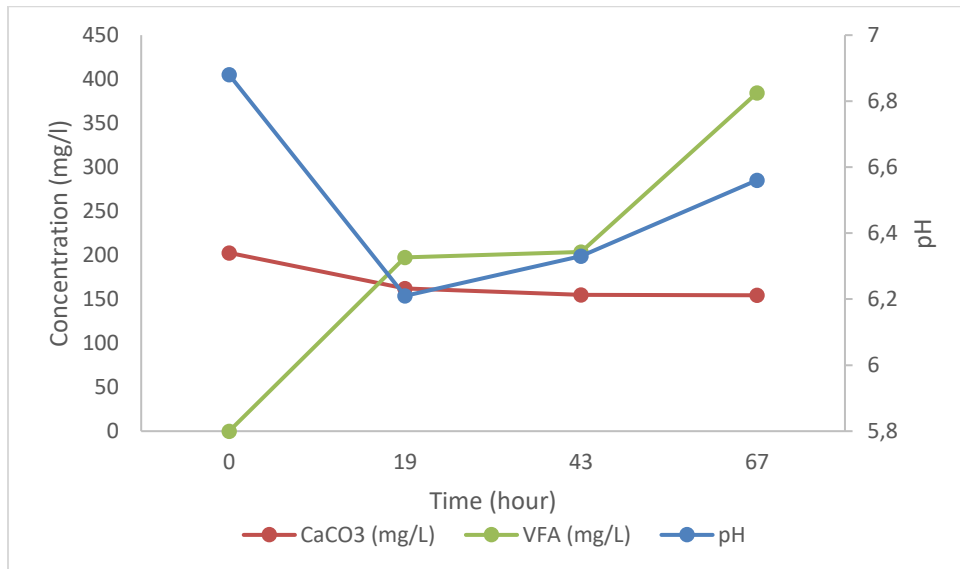
Figure 4.2: VFA, alkalinity and pH during fermentation test 0

Figure 4.2 show there is increasing of concentration VFA and decreasing alkalinity. This phenomenon is appropriate with the literature. Increasing VFA should be followed by decreasing alkalinity. Figure 4.2 and table 4.8 show the VFA yield after 67 hours was approximately 384 mg/l. This value reflects a low %TS in the sludge (0.80 %). As test 0 was the first fermentation test conducted, the result is lower than expected most probably caused by errors during titration. Another primary sludge fermentation test shows higher VFA concentration, as shown on table 4.10 and 4.15.
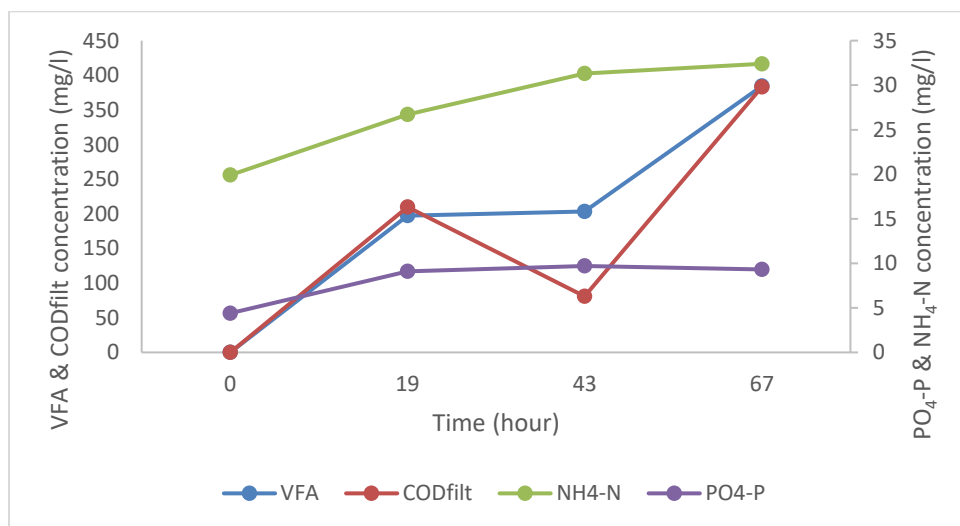
Figure 4.3: VFA, filtered COD, PO_4-P and NH_4-N from Test 0

Figure 4.3 show the correlation increasing VFA concentration with PO_4-P, NH_4-N and filtered COD. The increasing concentration VFA will cause an increasing concentration of PO_4-P, and NH_4-N. The increasing concentration of PO_4-P and NH_4-N because of the disintegration of proteins and cellular compounds during the fermentation test. This phenomenon indicates increasing the VFA concentration will increasing bacterial population and to optimize the P removal process in the EBPR.

Anaerobic Phosphate Release Test

Table 4.9 show anaerobe P release test with no VFA added and table 4.11 show anaerobe P release tests with various amounts of VFA added.

Table 4.9: P release with no VFA added from test 1, 2, and 3.

Time	Test 1					Test 2					Test 3				
	pH	CaCO3	VFA	COD$_{filt}$	PO$_4$-P	pH	CaCO$_3$	VFA	COD$_{filt}$	PO$_4$-P	pH	CaCO$_3$	VFA	COD$_{filt}$	PO$_4$-P
(minutes)		(mg/l)	(mg/l)	(mg/l)	(mg/l)		(mg/l)	(mg/l)	(mg/l)	(mg/l)		(mg/l)	(mg/l)	(mg/l)	(mg/l)
0	7.78	184	6	27	3	7.05	165	0	24	1	7.83	156	0	21	2
60	n.a	n.a	n.a	n.a	n.a	7.58	148	0	39	4	n.a	n.a	n.a	n.a	n.a
180	7.77	220	0	43	10	7.18	116	15	37	7	7.81	178	0	33	5
300	7.78	241	0	63	12	n.a	n.a	n.a	n.a	n.a	7.30	165	66	54	8

Without any added fermentation sludge, usually there is no production of VFA in the system. But from table 4.9 show some special case, VFA was produced as shown on test 1, at minute 0 show 6 mg/l; 15 mg/l on minute 180 on test 2 and 66 mg/l on test 3, minute 300. This could be because of the bacteria was start produce at that time. Also, probably because of random error during titration. Figure 4.4 and 4.5 are to show the result from table 4.9 (Test 1).
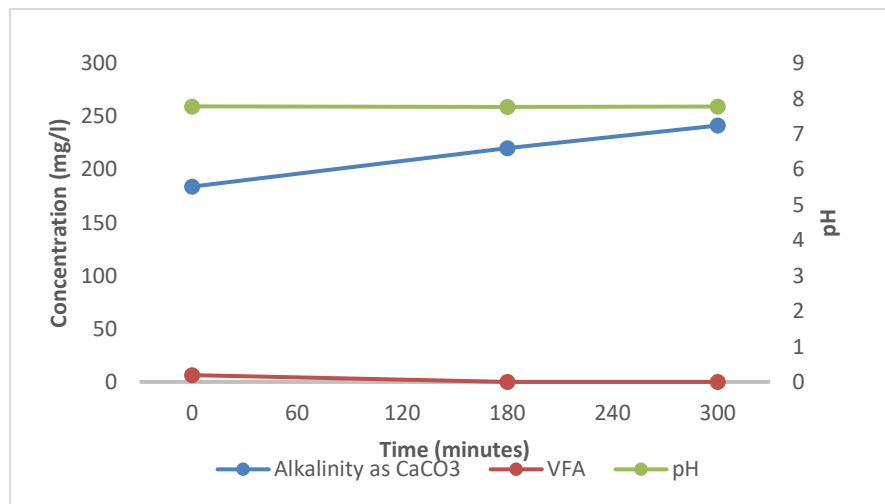
Figure 4.4: VFA, alkalinity, and pH without added fermented sludge
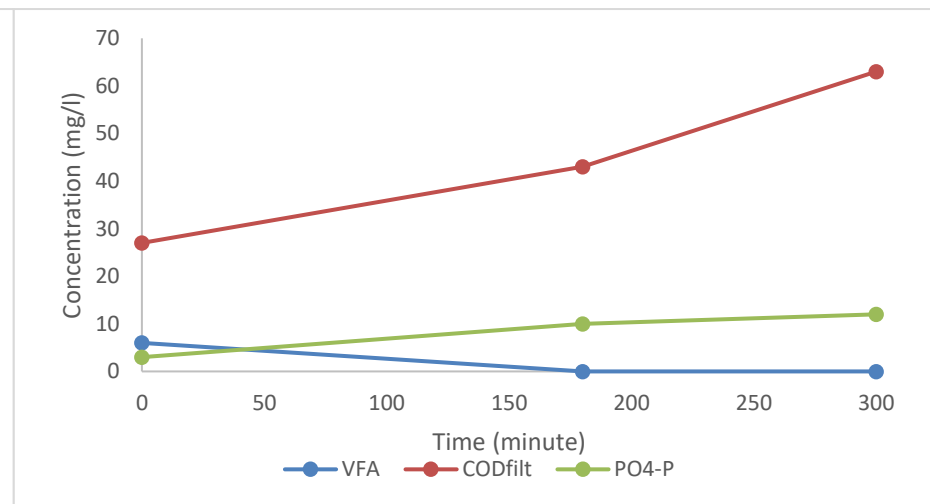
Figure 4.5: VFA, COD$_{filt}$, and PO$_4$-P without added fermented sludge

Figure 4.4 and 4.5 show the EBPR sludge in anaerobic condition without add fermentation sludge. The VFA concentration decrease by the time because there are not added any fermentation products as a food in the system. Alkalinity, filtered COD and PO_4-P shows increasing values during the tests. An increase in the concentration of PO_4-P indicate that even without adding VFA in the system there is a slightly response of bacteria from the sludge.

Next table and figure will show the change in the system with added fermentation by volume respectively. Table 4.10 show the VFA concentration from fermentation test 1, 2, and 3. Filtrated from fermentation test 1, 2, and 3 (table 4.10) were used as the substrate in anaerobe P release test by variations concentration added (30, 50, 70, and 100 ml) as show on table 4.11.

Table 4.10: VFA concentration, alkalinity as $CaCO_3$ from test 1, 2, & 3

Date	Test No.	Duration (day)	pH	CaCO3 (mg/l)	VFA (mg/l)	TS (%)
29.jan	1	2	6,12	13,9	532,3	0,92
04.feb	2	3	5,87	-10,2	972,4	1,49
12.feb	3	2	6,24	70,4	566,8	1,57

Table 4.11: The pH, VFA, Alkalinity as CaCO₃, PO₄-P, and COD_{filt} for each variations volume fermented added

Time (minutes)	VFA Added: 30 ml					VFA Added: 50 ml				
	pH	$CaCO_3$ (mg/l)	VFA (mg/l)	COD_{filt} (mg/l)	PO_4-P (mg/l)	pH	$CaCO_3$ (mg/l)	VFA (mg/l)	COD_{filt} (mg/l)	PO_4-P (mg/l)
5	7.88	215	30	80	4	7.26	129	127	292	9
60	7.66	202	82	158	9	7.47	99	128	254	9
120	7.77	225	39	70	10	7.43	104	101	269	11
180	7.93	166	44	66	9	7.20	95	95	237	12
240	7.85	186	59	81	11	7.39	106	105	257	15
300	7.76	194	49	84	11	n.a	n.a	n.a	n.a	n.a

Time (minutes)	VFA Added: 70 ml					VFA Added: 100 ml				
	pH	$CaCO_3$ (mg/l)	VFA (mg/l)	COD_{filt} (mg/l)	PO_4-P (mg/l)	pH	$CaCO_3$ (mg/l)	VFA (mg/l)	COD_{filt} (mg/l)	PO_4-P (mg/l)
5	7.70	206	92	178	7	6.99	71	276	599	15
60	7.85	171	45	66	6	7.27	80	241	529	15
120	7.73	207	62	155	9	7.19	66	280	504	15
180	7.83	187	30	154	11	7.23	93	249	521	17
240	7.72	204	56	165	13	7.14	74	232	515	18
300	7.81	181	96	152	13	n.a	n.a	n.a	n.a	n.a

Figure 4.6 shows the VFA concentrations, alkalinity as CaCO$_3$, pH, filtered COD and PO$_4$-P released by adding 30 ml of fermented sludge from test 1.
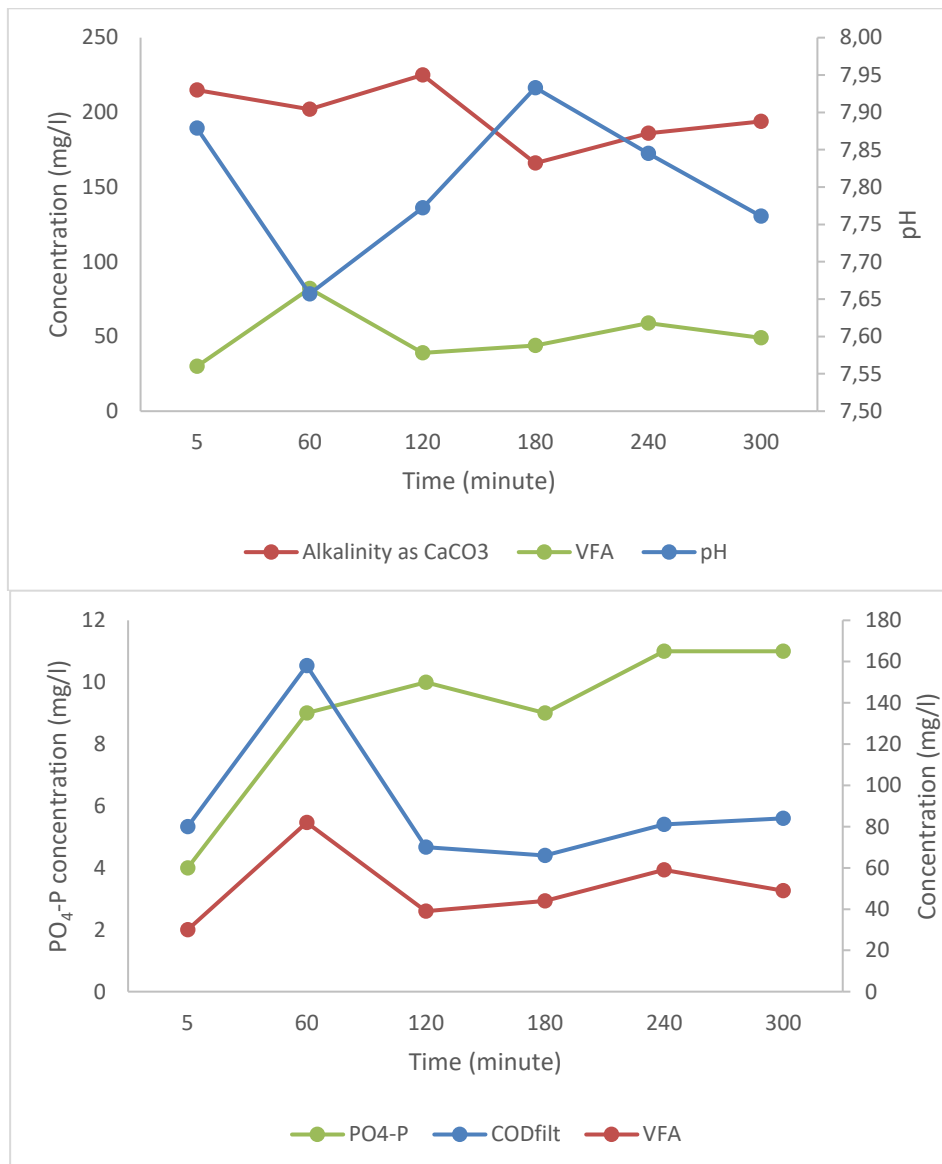
Figure 4.6: Added 30 ml fermented sludge

From figure 4.6 show the increasing PO$_4$-P and filtered COD concentration by added 30 ml fermented sludge. As a result of PO$_4$-P release by the biomass. Compare to figure 4.5, increasing PO$_4$-P concentration slightly higher. This indicates the increasing activity of bacteria in the system.

Figure 4.7 shows the VFA concentration, alkalinity as CaCO₃, pH, filtered COD and PO_4-P released by adding 50 ml of fermented sludge from test 2.
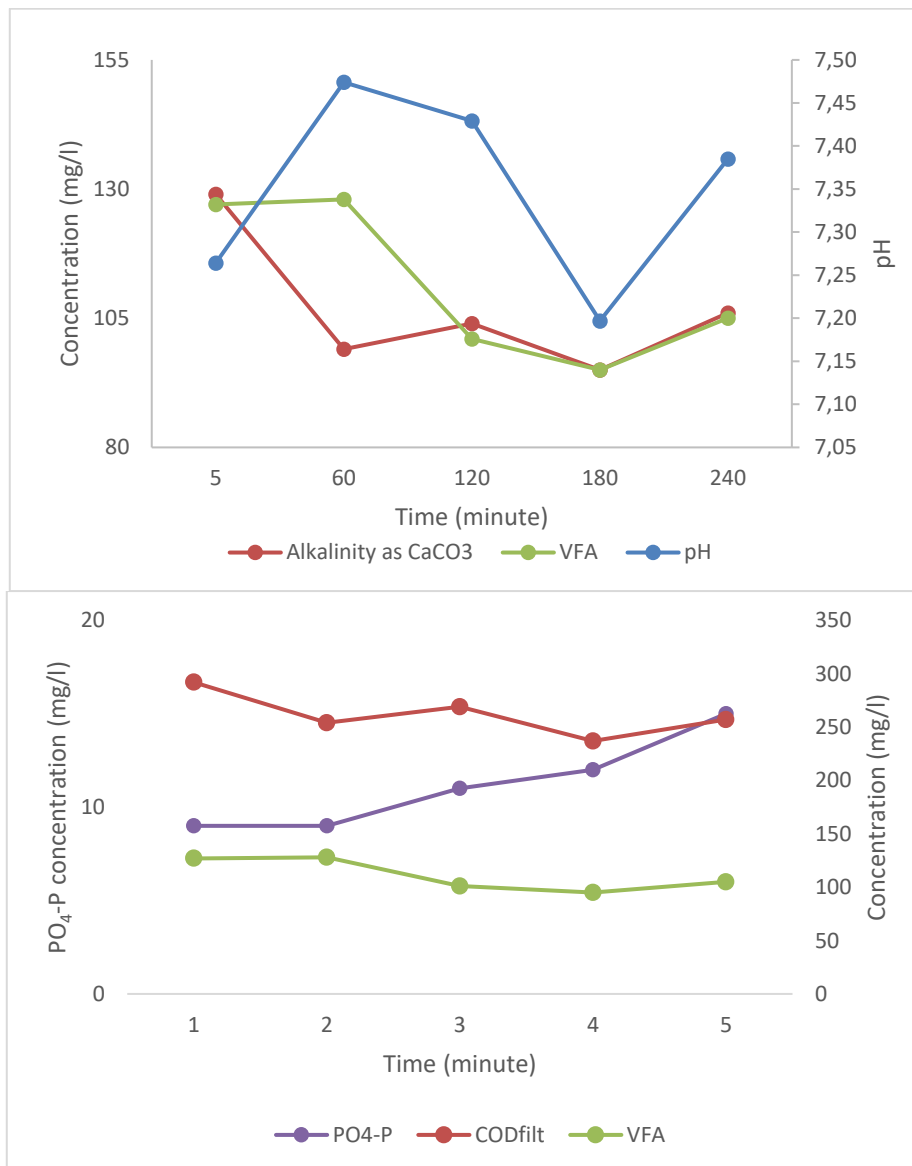
Figure 4.7: Added 50 ml fermented sludge

The concentration PO_4-P increase as volume VFA added increase. Figure 4.7 compare to figure 4.6 show that increase of concentration of PO_4-P is slightly higher.

Figure 4.8 shows the VFA concentration, alkalinity as CaCO₃, pH, filtered COD and PO₄-P of effluent wastewater with adding 70 ml fermented sludge from test 1. The concentration of PO₄-P is increasing with increasing volume VFA added as show on figure 4.6 and 4.7 as well.
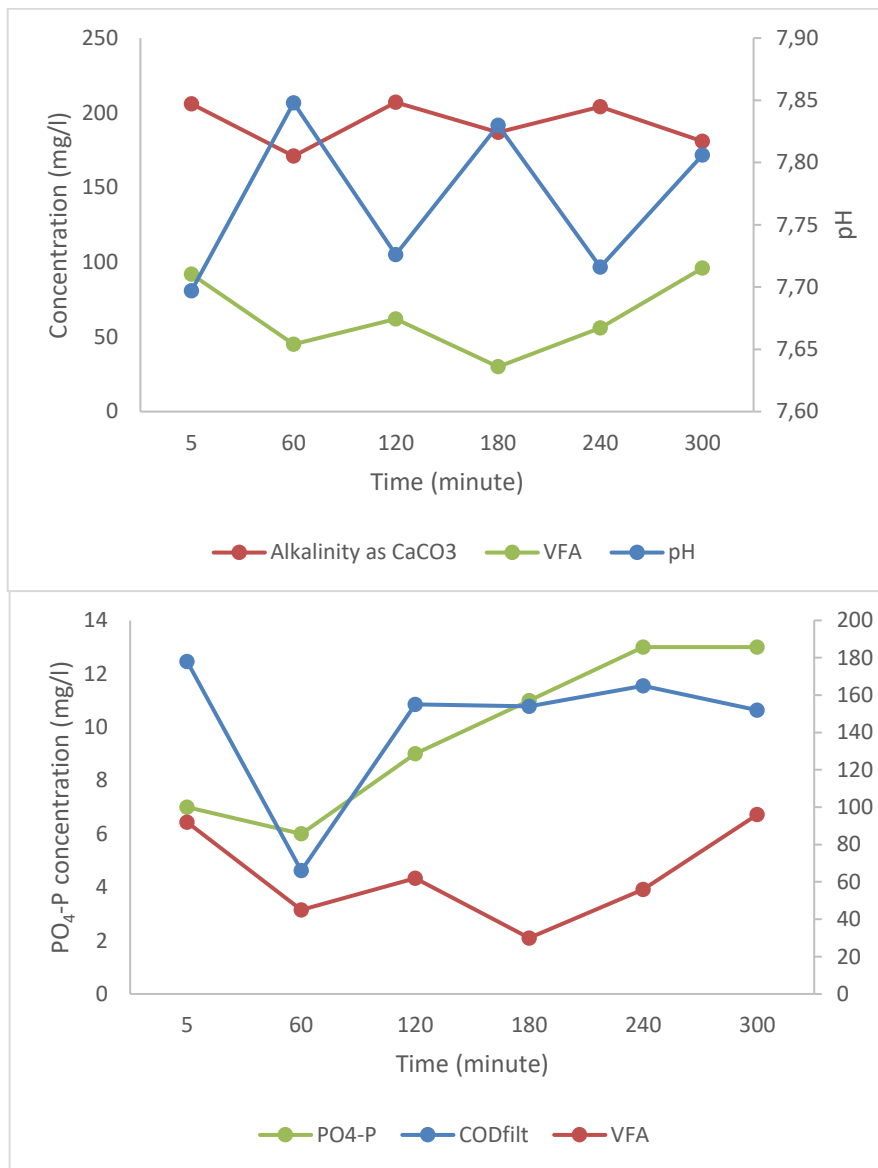
Figure 4.8: Added 70 ml fermented sludge

Figure 4.9 shows the VFA concentration, alkalinity as CaCO$_3$, filtered COD and PO$_4$-P of effluent wastewater with added 100 ml fermented sludge from test 2. The phenomena of increasing concentration PO$_4$-P was observed in figure 4.6 – 4.8 as well. The PO$_4$-P concentration is highest if compare to added VFA 30 ml, 50 ml, and 70 ml.
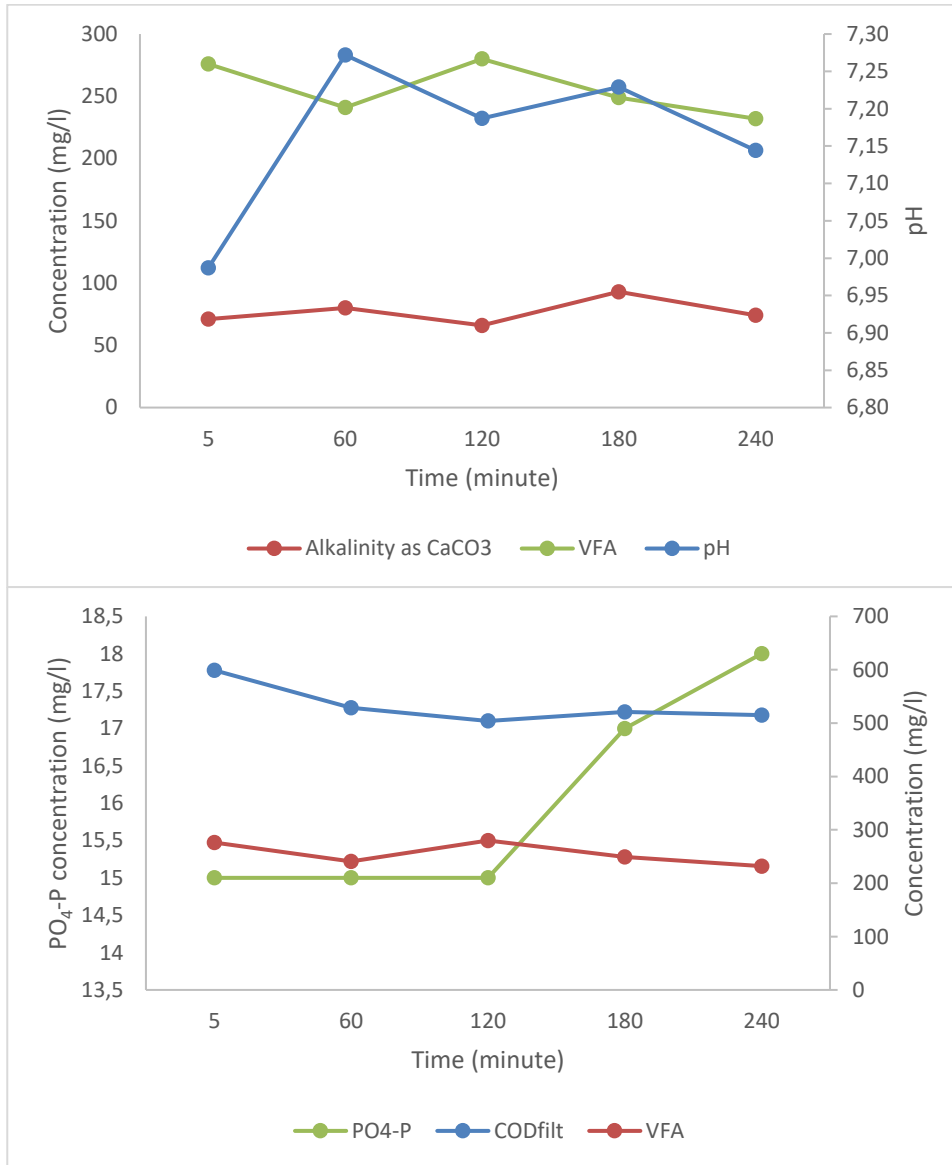
Figure 4.9: Added 100 ml fermented sludge

Figure 4.6 – 4.9 show the VFA effect on PO$_4$-P release when added variatiable volumes between 30-100 ml to the EBPR sludge.
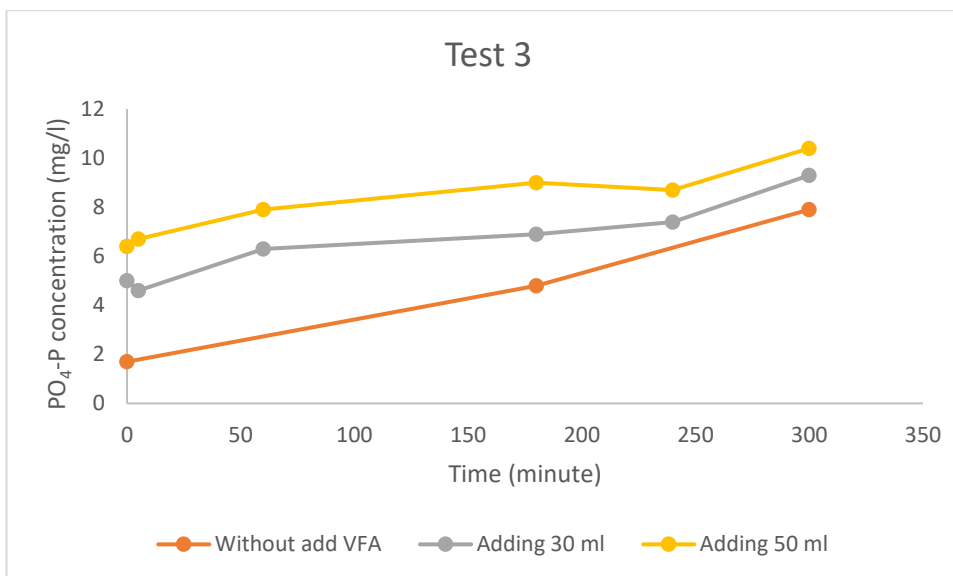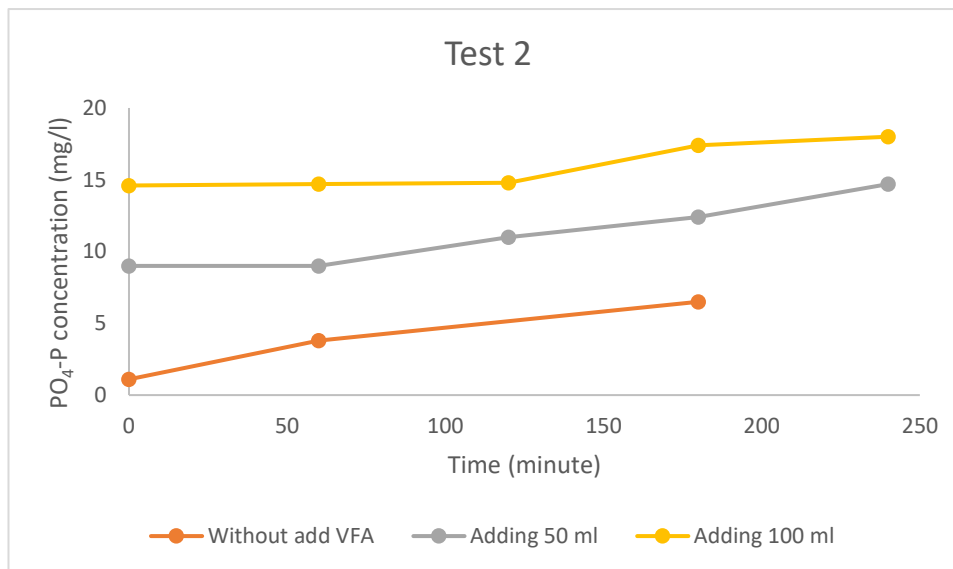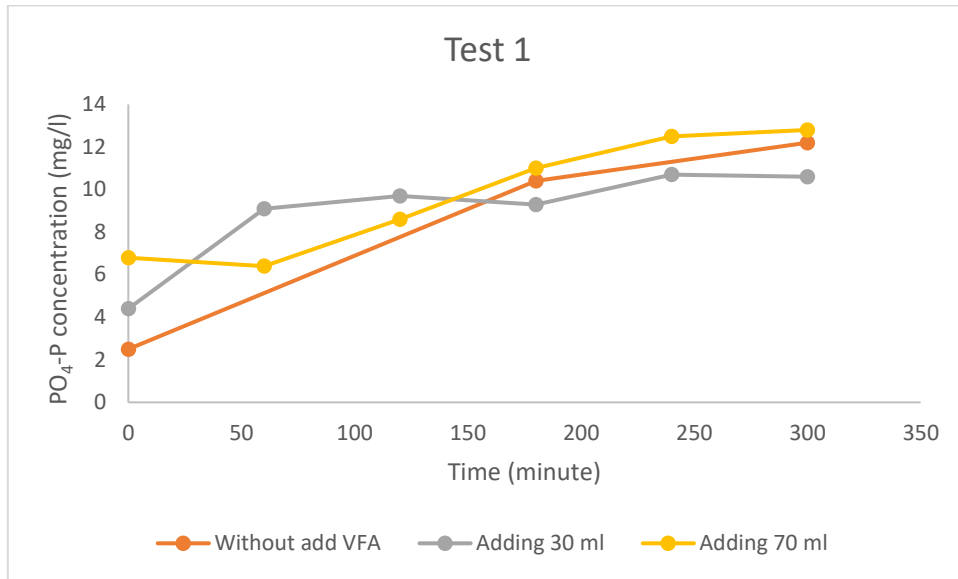
Figure 4.10: Increasing PO₄-P concentration
with variations VFA volume added (0 – 100 ml) from test 1-3.

Figure 4.10 show PO_4-P concentrations with variations in added VFA volume from Test 1-3 with %TS and VFA concentration respectively. This test was pH-uncontrolled, however from figure 4.10 show increasing PO_4-P concentration by increasing volume VFA added. So, the conclusion of this test is primary sludge produced VFA with a positive effect on the EBPR sludge.

4.3   Overview Phosphate Release in the Bioreactor and Batch Test

EBPR activity in bioreactor L1

Figure 4.11 show the phosphate concentration at different sampling points in the biological reactor line 1. This show the P release and uptake as it should be, but the P release in the settling tank, reduces the P removal efficiency.

There is an increase in PO_4-P concentration in the anaerobic reactor compared to the influent. This is because of the release of phosphate by the PAOs. An 1 PO_4-P concentration is highest compared to the other anaerobic reactor because the influent in An 1 is from RAS.
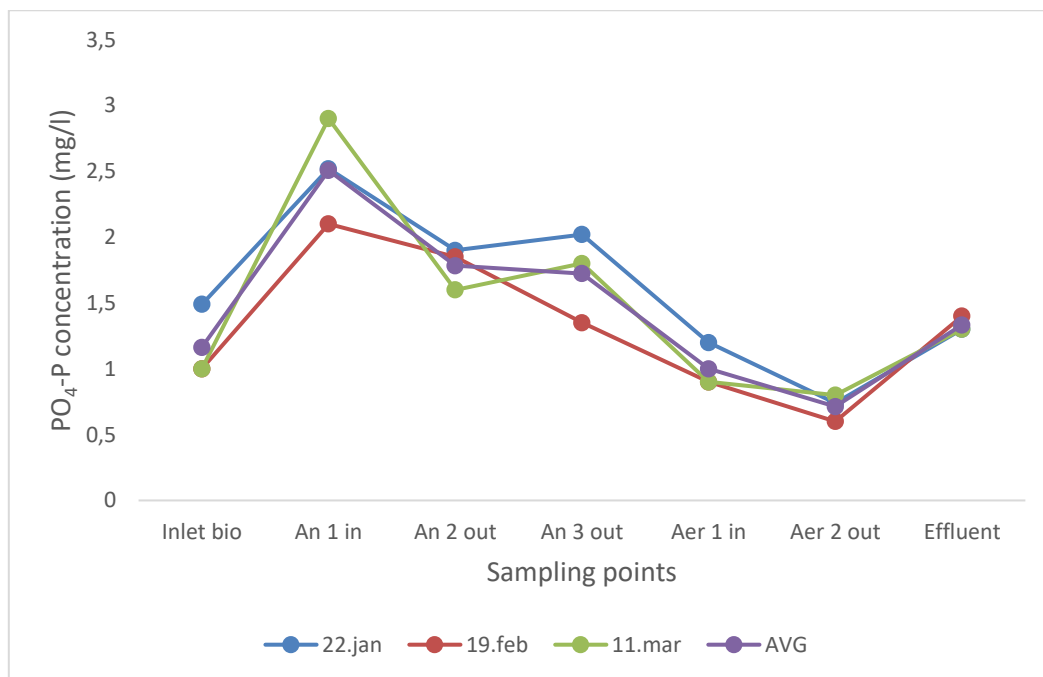
Figure 4.11: Evolution of the PO4-P concentration in the bioreactor line 1

The fact PO_4-P concentration decreases in the aerobic reactor compared to the anaerobic reactor is due to phosphate uptake and accumulation by the PAO organisms. This show phosphorus removal from the influent until effluent because of the accumulation carried out by the PAO biomass formed.

The phosphate concentration in the effluent wastewater is higher compared to aerobic reactor effluent. Phosphate concentration in the effluent should be same as Aer 2 outlet. This indicate that phosphate is released from the sludge in the settling tanks. This can happen because of long retention

time and ineffective sludge return and/or sludge waste in settling tank. This occurrence is supported by data from measurements of the sludge blanket level in settling tank, this will be reviewed on section 4.4.

During the study, there have been adjustment on the line 1 RAS pump. The RAS pump was set to 25% of the influent flow, as the normal opening is 40%. The result from this adjustment show a change but not so significant as shown on table 4.12 and figure 4.12.

Table 4.12: Comparation at the RAS pump set 40% and 25% of the influent flow

Position	Flow (m^3/h)		TSS (mg/l)		VSS (mg/l)		PO$_4$-P (mg/l)		COD$_{filt}$ (mg/l)	
	40%	25%	40%	25%	40%	25%	40%	25%	40%	25%
Inlet bio	1656	1260	226	49	205	43	1.4	1.6	32	28
An 1	800*	220*	2243	3130	1281	2635	4.0	5.4	38	49
An 2	2456**	1480**	1188	1462	988	1238	2.9	3.1	40	26
An 3	2456	1480	1471	1375	1233	1167	2.4	2.3	29	25
Aer 1	2456	1480	1542	1388	1304	1125	1.8	1.5	22	27
Aer 2	2456	1480	1568	1408	1314	1176	2.0	1.3	31	21

*RAS; **RAS+inlet
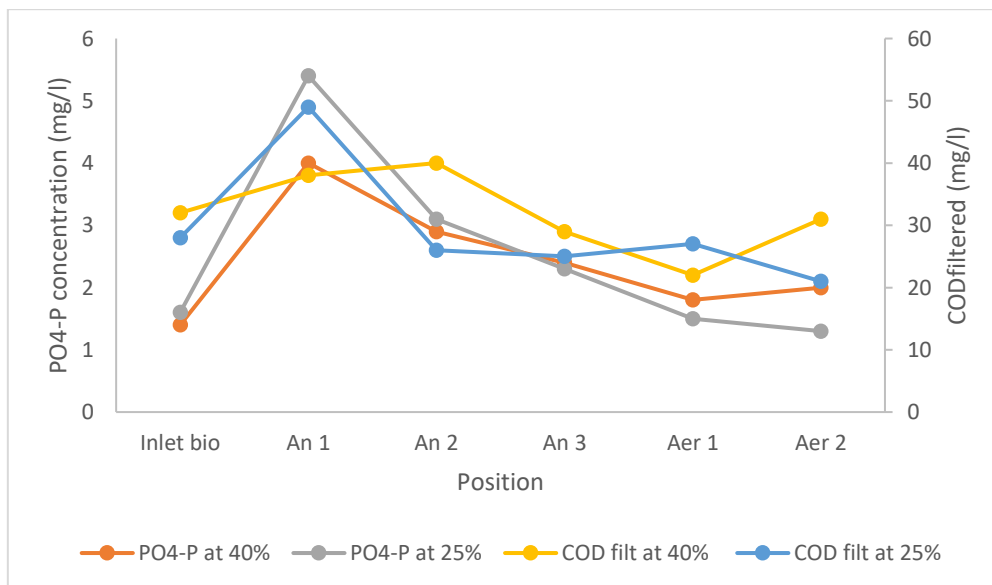
Figure 4.12: Comparation PO$_4$-P concentration and COD$_{filt}$ concentration at different RAS pump setting

Figure 4.12 show that PO$_4$-P concentration in the anaerobic zone after adjustment are higher than before adjustment and lower in aerobic zone, this means that the reduction of PO$_4$-P is better after the

adjustment. The COD_{filt} concentration show not so significant difference. However, the COD_{filt} concentration decreased after adjustment at Aer 2 position compared to before adjustment respectively. The conclusion of adjustment of RAS at 25% is better than at 40% but still need to do more test on this adjustment.

The phosphate release and uptake rates through the bioreactor L1 are presented in table 4.13 and figure 4.13. Observed the three sample dates and the average.
The formula used for calculation and all results from phosphate release and uptake rates presented in appendix C.1.

Table 4.13: P release and uptake through L1

| | P release / P uptake (mg P/g VSS h^{-1}) | | | | | | | |
| | 19.feb | | 26.feb | | 11.mar | | AVG | |
	P release	P uptake	P release	P uptake	P release	P uptake	P release	P uptake
An 1	0.79		2.16		1.00		1.32	
An 2	1.67		1.73		1.32		1.57	
An 3		-1.73		-1.06	0.64			-0.72
Aer 1		-0.46		-0.40		-1.32		-0.73
Aer 2		-0.31	0.13			-0.13		-0.10

Date measurement	P release / P uptake (mg P/g VSS h^{-1})
19.feb	-0.04
26.feb	2.56
11.mar	1.52

The rates in all anaerobic reactors were expected to be positive (P release), but in An 3 it show mostly negative values. This indicate that An 3 is not in exactly anaerobic condition, the PAOs take up phosphate rather than releasing. Under this condition, the OHOs will not convert the fermentable COD to VFAs, but utilize it for energy and growth with oxygen. Due to not enough VFA will be available for the PAOs, because of that it will give affect to the overall P removal.

The highest P release should be highest in An 1 because of the flow from RAS, but from table 4.13 and figure 4.13 it show the highest P release mostly in An 2. This indicate that there is substrate supplied from An 1 to An 2.

The P uptake show in Aer 1, Aer 2 and An 3. The uptake rates of Aer 1 and Aer 2 show that most of the phosphate is taken up at the beginning of the aerobic reactor. This indicate that the PHB utilization and PAO growth is higher in Aer 1.

Figure 4.13 show the phosphate release and uptake rates. The trends of the P release and uptake rates observed from three sampling dates and the average.
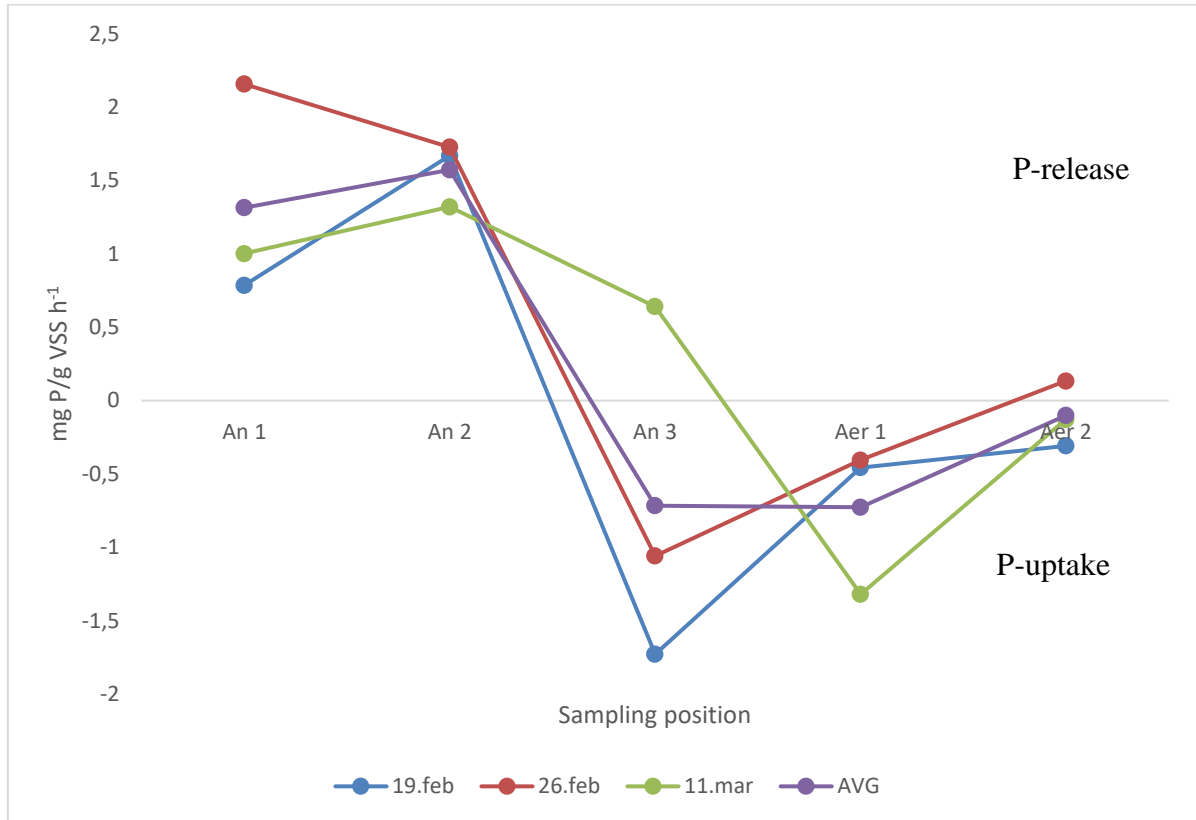
Figure 4.13: PO$_4$-P release and uptake rates through the bioreactor L1

The variation rates of An 2 and An 3 could be caused by oxygen in reactor and RBCOD in An 3. Under this condition, the PAOs will regenerate the poly-P chains and the OHOs will oxidize rather than ferment the RBCOD in An 3.

Referring to Janssen et al. (2002), the classification of the biological phosphorus removal sludge is related to the magnitude of the release and uptake rates as presented in table 4.14

Table 4.14: Classification of biological P removal sludge based on the P release and P uptake rate (Janssen et al., 2002).

Release or uptake rate (mg P/g VSS h^{-1})	Classification
<3	Moderate
3 – 7	Good
>7	Very good

As all the calculated P release rates on table 4.13 are below 3 mg P/g VSS h^{-1}, that mean the EBPR sludge is classified as ***moderate***. This is indicated as negligible biological P activity as a result of a low fraction of PAOs in the sludge. The low P release rate indicate there is a low amount or not enough VFA available. The organic material could be degraded before the PAOs can consummate it and cause a low P release rate. Furthermore, this data also supports by Joh Kang et al. (1991), which mentioned a favourable P release rate is above 2.4 mg P/g VSS h^{-1}. Anyhow, the good/very good biological P removal classification does not guarantee that the P removal efficiency in the system is high (Janssen et al., 2002). Still among other factors such as characteristics of wastewater; COD:P ratio, and the magnitude of COD availability to PAOs in the anaerobic zone, and the internal phosphate load (Janssen et al., 2002).

Batch Test

The effectivity of EBPR in batch experiments by added fermented sludge and without added fermented sludge were studied. Tests have been done with concentrated and unconcentrated sludge and with added fermented sludge at volumes of 0, 30, and 50 ml from test 4-6. VFA concentration, alkalinity, pH and TS from fermented sludge test 4-6 is shown in table 4.15.

Table 4.15: VFA concentration, alkalinity as CaCO₃ from test 4-6

Date	Test No.	Duration (day)	pH	CaCO$_3$ (mg/l)	VFA (mg/l)	TS (%)
18.feb	4	2	6.52	94	581	1.20
25.feb	5	2	6.17	4	578	1.30
04.mar	6	2	6.21	64	551	1.38

Figure 4.14 is showing the PO$_4$-P uptake and release in the batch experiment without any added fermented sludge. From figure 4.14, on date Feb 13th and 20th are concentrated sludge samples used in the test and on date Feb 27th and March 6th are without concentrated sludge samples. Concentrated sample has TSS of 3000-4000 mg/l and unconcentrated is 1000-2000 mg/l TSS respectively (table 3.3). The tests were started with anaerobic process for 180 minutes and aerobic process after.

Concentrations of PO$_4$-P increased during the anaerobic conditions. This show the rate of anaerobic P release in anaerobic conditions. Hypothesised this means the P release to acetate uptake ratio would be affected by variation in the PAOs and GAOs relative populations. A higher proportion of PAOs will maximize the quantity of acetate taken up and PO$_4$-P released.

The graph on date Feb 13th and 20th shows the similar curved shapes which is means the alteration are almost the same. But for the graphs on Feb 27th and March 6th, it shows that the alteration

take more time and with lower concentrations of PO_4-P compared to 13th and 20th Feb. Due to the concentrated samples, the process will be faster and higher PO_4-P release and uptake is observed compared to not concentrated samples.
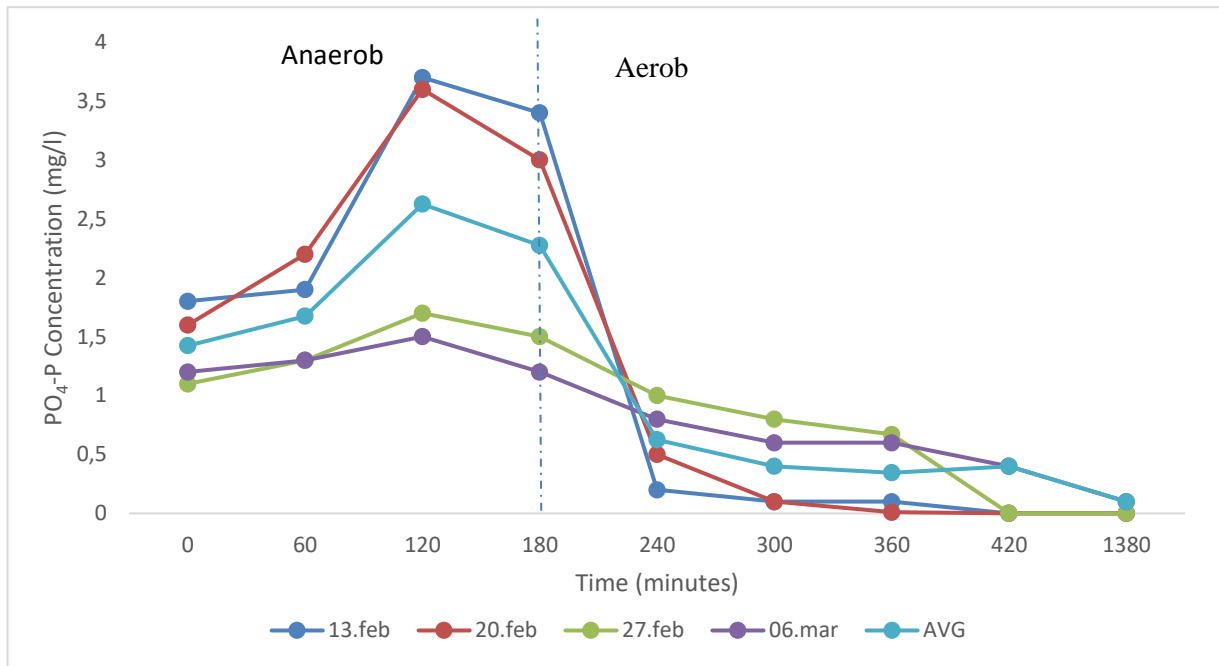
Figure 4.14: Batch test without added fermented sludge

Next analyse is added 30 ml VFA to concentrated and unconcentrated sample. As shows on figure 4.15.
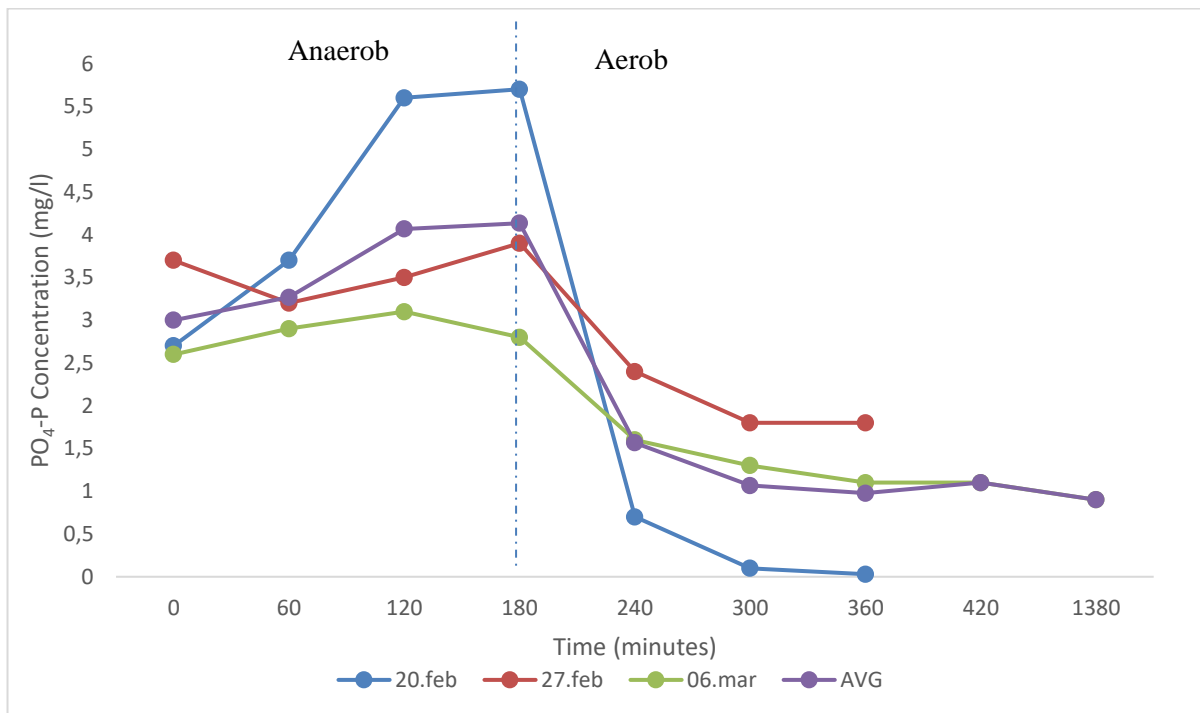
Figure 4.15: Batch test, added 30 ml fermented sludge.

Concentrated/unconcentrated samples were added 30 ml fermentation sludge, and the alteration is faster than the samples without added fermentation sludge. Effluent samples collected on Feb 20th were concentrated, and on Feb 27th and March 6th were unconcentrated. However, the condition in the actual EBPR is unconcentrated so it is important to analyse on this condition. From figure 4.15 aerobic condition is started after 180 minutes. The graph on Feb 20th was the highest and dropped immediately compared to the others. It was because they were concentrated samples.

Figure 4.16 show how the alteration, if the samples were added 50 ml of fermented sludge. Same as figure 4.14 and 4.15, sludge samples collected on Feb 20th were concentrated, and on Feb 27th and March 6th were unconcentrated. From this experiment, it was expected faster release and uptake of PO_4-P compared to samples without added and 30 ml fermented volume added, but the figure shows not as expected. Figure 4.16 show that by adding 50 ml fermented sludge it does not show that the phosphate is removed faster than at addition of 30 ml. This indicate that the volume of added VFA to the system would have some optimum conditions in this region.
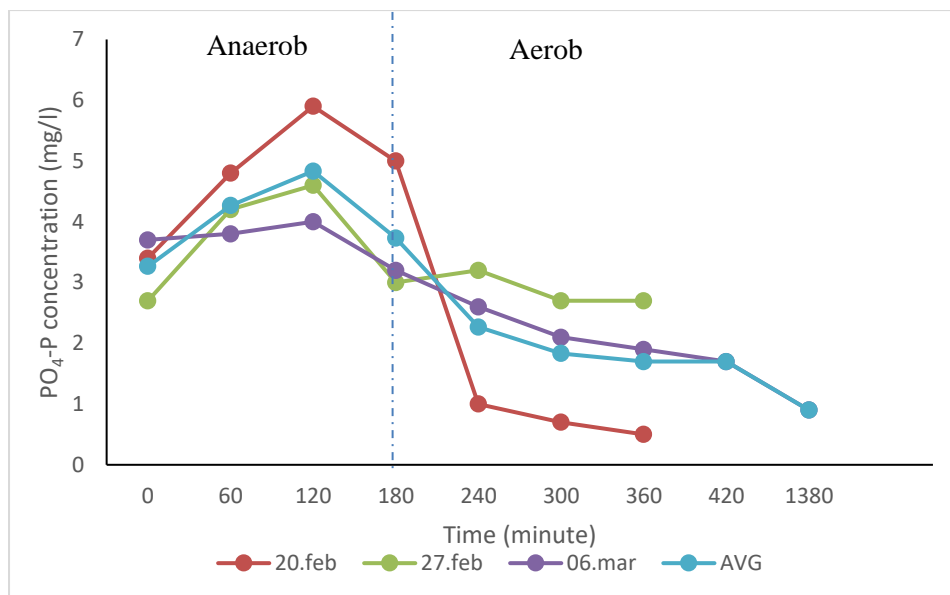
Figure 4.16: Batch test, added 50 ml fermented sludge.

From the batch tests, the conclusion is that phosphate reduction the biological line was quite high, based on the phosphate release at anaerobic condition and uptake at aerobic condition, resulting in that the effluent concentration become close to zero at aerobic condition.

4.4 Sludge blanket level in settling tanks

The settling tanks at SNJ WWTP are rectangular with horizontal flow pattern as show on figure 4.17. This thesis focus on settling tanks 1, 2, 3, and 4 continuity from biological reactor line 1. All data from settling tanks presented in appendix D.
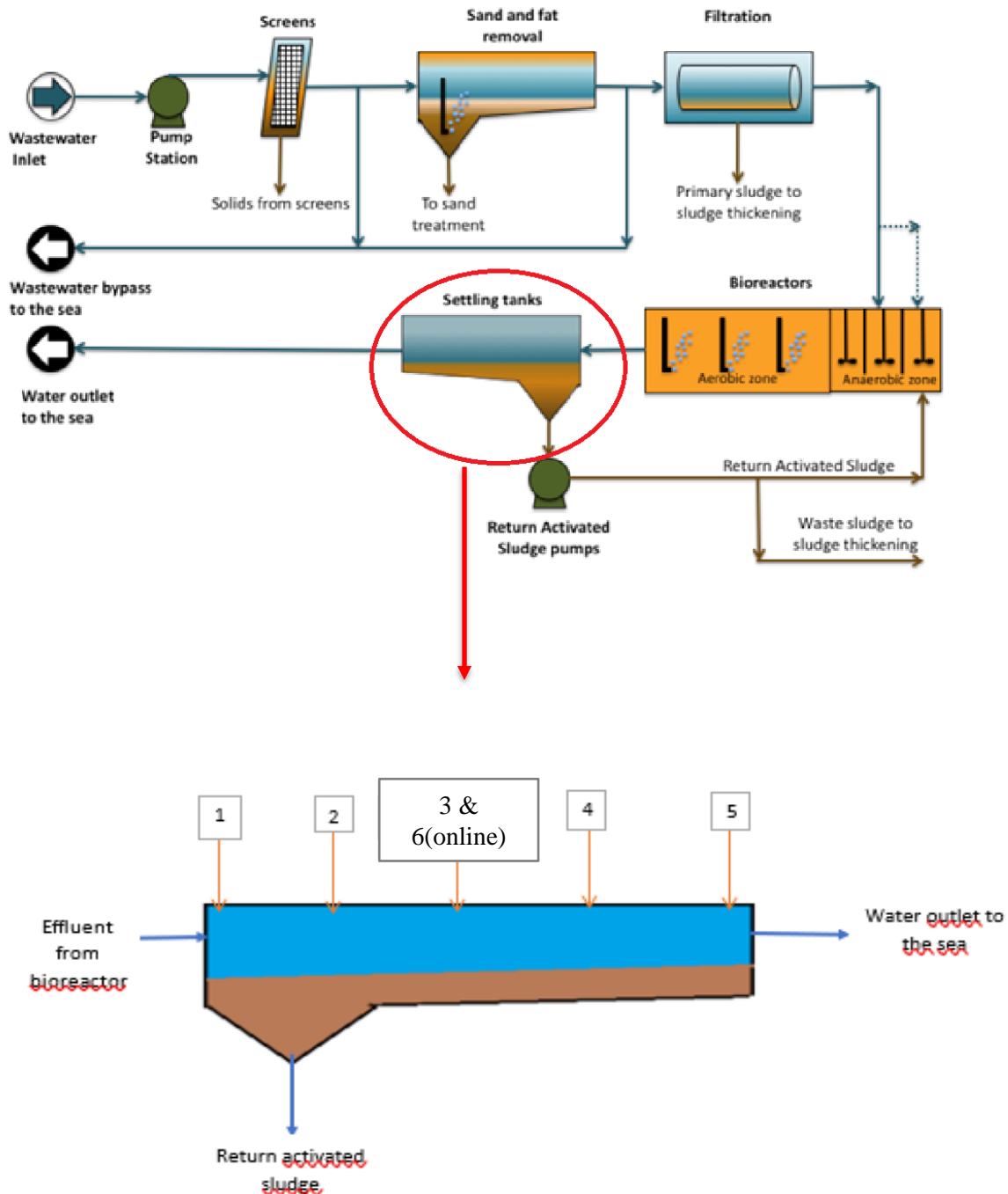
Figure 4.17: Sludge blanket samples position in settling tank IVAR SNJ WWTP

The measurement point in settling tank show on figure 4.17. Point 1,2,3,4, and 5 were measured directly from the settling tank, while 6 is online measurement from the display.

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The settling tanks are an important unit in the activated sludge biological wastewater treatment. As the final step in the process, the settling tanks should produce a clear effluent. Meanwhile, the settling tanks are also important to sufficient thickening sludge to reach highly concentrated return sludge and biomass within the bioreactor.

PO_4-P concentration in effluent should be the same as in the effluent of the aeration tank (Aer 2). But from figure 4.12 (section 4.3) the PO_4-P concentration in effluent is higher than Aer 2. This case indicates there is secondary phosphate release from the sludge in the settling tank. It can happen if long retention time and ineffective sludge return and/or wasting from the settling tank, resulting in anaerobic conditions and PO_4-P release. During sample period February – March the sludge level is quite high and SVI at SNJ in range 79 – 100 as shown on table 4.16, the average is 90 ml/g. The high sludge blanket levels indicate there is a problem of accumulation of sludge. This is shown in figures in this section.

Table 4.16: the MLSS and SVI data from February – March 2019

Date	MLSS (mg/l)	SVI (ml/g)
18.02.2019	1638	79
21.02.2019	1836	87
27.02.2019	1396	100
28.02.2019	1424	91
01.03.2019	956	95

According to Rumbaugh (2019), general SVI ranges guidelines are:
- SVI < 80 ml/g, indicates fast settling, if supernatant is turbid low SVI indicates dense, old sludge settling characteristics.
- 100 – 200 ml/g, this range means most activated sludge systems operate seem to produce a clear, high-quality effluent. The sludge typically settles slower and traps more particulate matter as it forms a uniform blanket before settling.
- SVI > 250 ml/g means the sludge settles very slowly and compacts poorly in the settleability test. It is indicated by light and fluffy MLSS.

Based on guidelines for SVI above, it is indicated that the sludge from secondary settling in table 4.16 are within typical/good ranges. This mean that the high sludge blanket in settling tanks is not because of poor sludge settling characteristics (SVI) but unfavourable hydraulic conditions (short- circuiting) and insufficient capacity of the sludge scrapers. Fermentation may occur within the sludge, and the

RBCOD will stimulate PO$_4$-P release. The secondary release in the settling tanks will reduce the poly-P, which will be available for carbon storage in An 2 and An 3, and thus reducing the overall P removal efficiency.

The other dates from table 4.16 indicate where the most activated sludge system operate. It show better sludge settling characteristics. However, the range is just guidelines, still need to review how the settling tanks functions in the system and the quality of the sludge.

Figure 4.18 – 4.20 shows the sludge blanket level in the settling tanks number 1-4 during period January – March 2019. Figure 4.18 show the sludge level in secondary settling tank number 1-4 at January 2019. Reducing of sludge blanket level not as expected. The figure shows highest level at inlet end, and reducing sludge level towards the effluent.
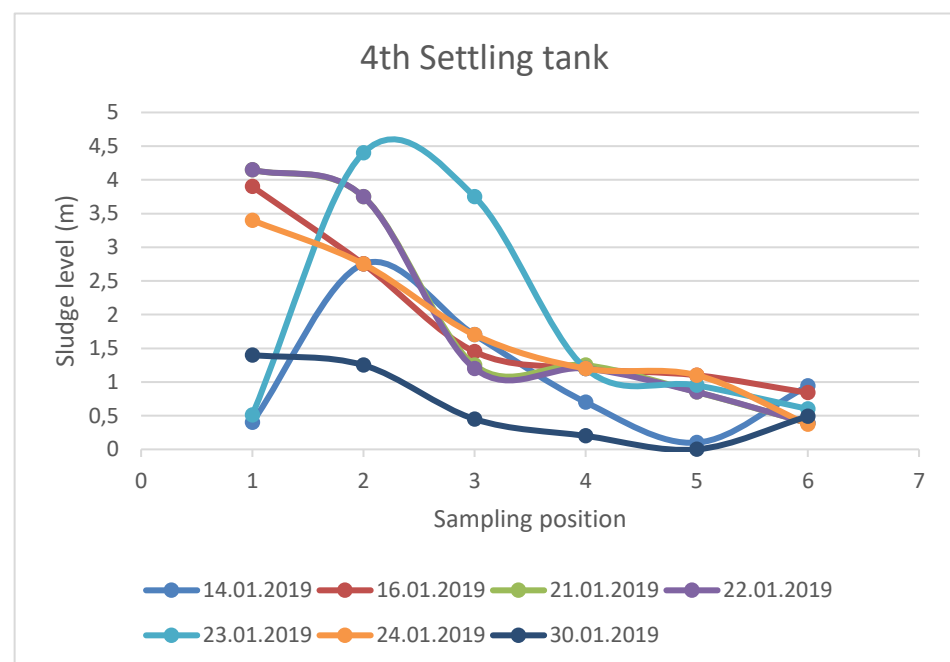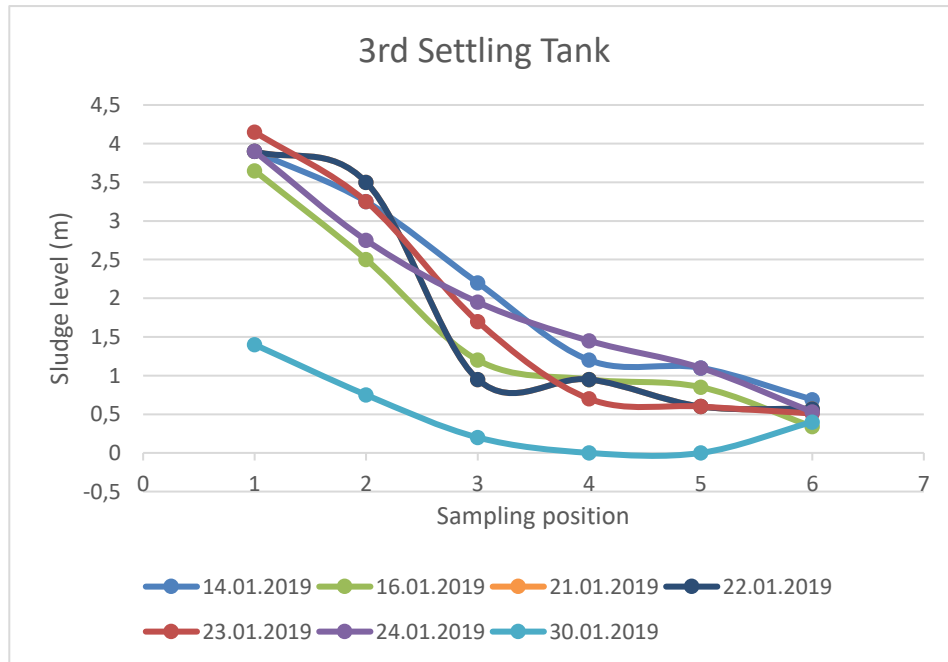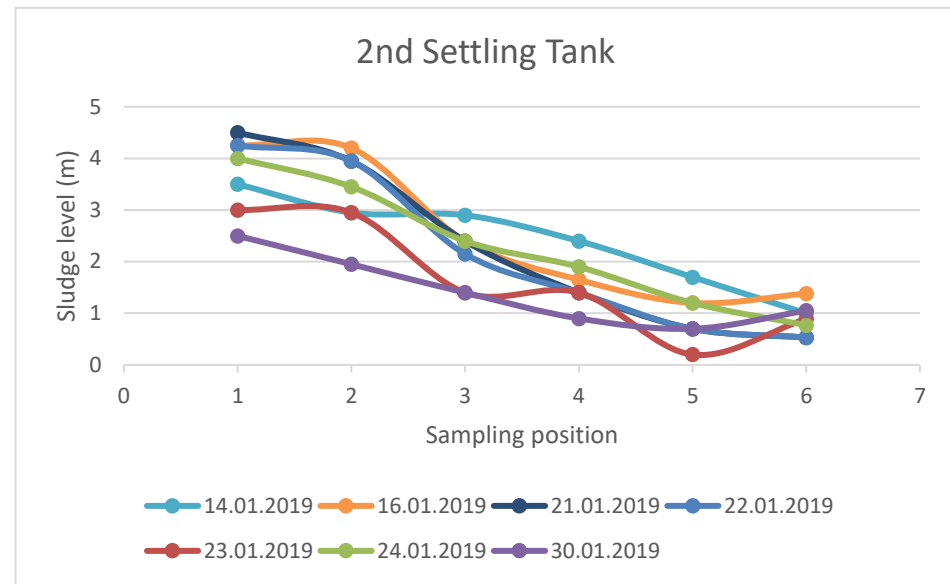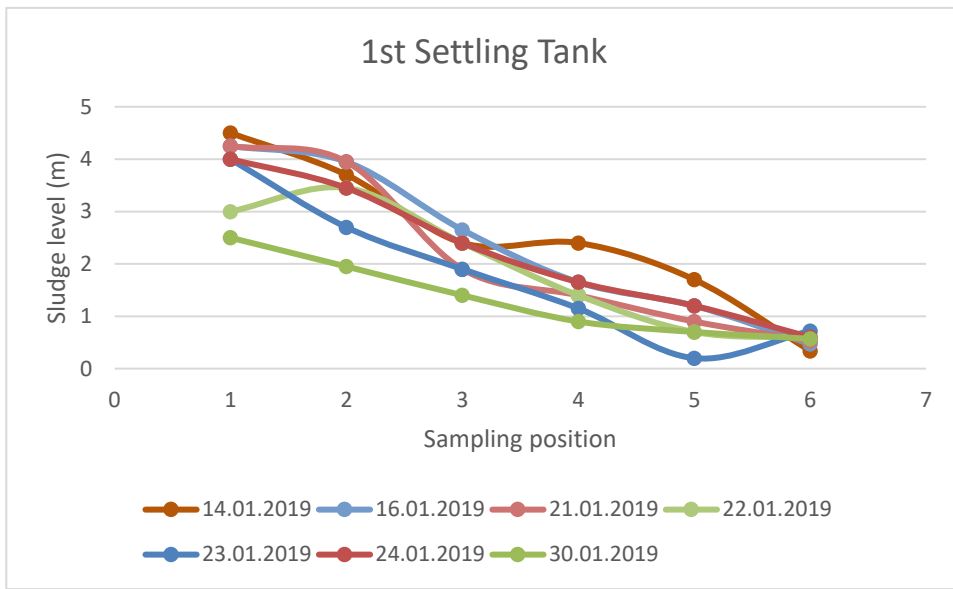
Figure 4.18: Sludge blanket level in settling tank 1, 2, 3 and 4; January 2019.(*6: Online, sludge blanket level shown on the display)

Next figure 4.19 and 4.20 show the sludge blanket level periods February – March 2019. Similar as figure 4.18, the sludge blanket level was not reduced as expected and show high sludge level. But on figure 4.18, 3rd settling tank show better than other. Based on figures 4.18 and 4.19, 3rd settling tank show better condition of sludge level compare to other settling tanks. But in March period (figure 4.20), the 3rd settling tank show not as expected. However, the expected settling tank with low sludge blanket level cannot represented from this thesis project.

On March analyses, there was adjusted time setting on scraper in secondary settling tanks. Adjustment was 40 seconds movement and 10 seconds waiting time. The purpose of adjustment is to make more effective in secondary settling tanks and reducing sludge in the tank . The results of adjustment shown on figure 4.20, on date 8-13 March. The result of adjustment was not as expected; the sludge blanket level still high. If we review by SVI, SVI average is 90 ml/g respectively, which indicated active sludge system operated. Hence the sludge blanket level was high although adjusted lower waiting time can be caused by problem with sludge circulation in the tanks.

The sludge levels in February – March was generally lower than in January. This could be because of variation in flow rate, sludge characteristics and operational disturbances.
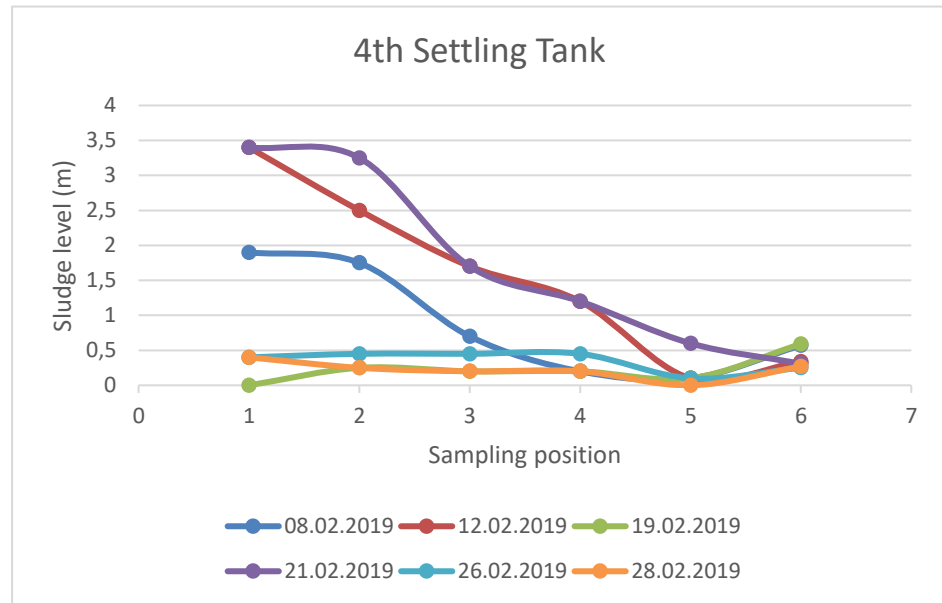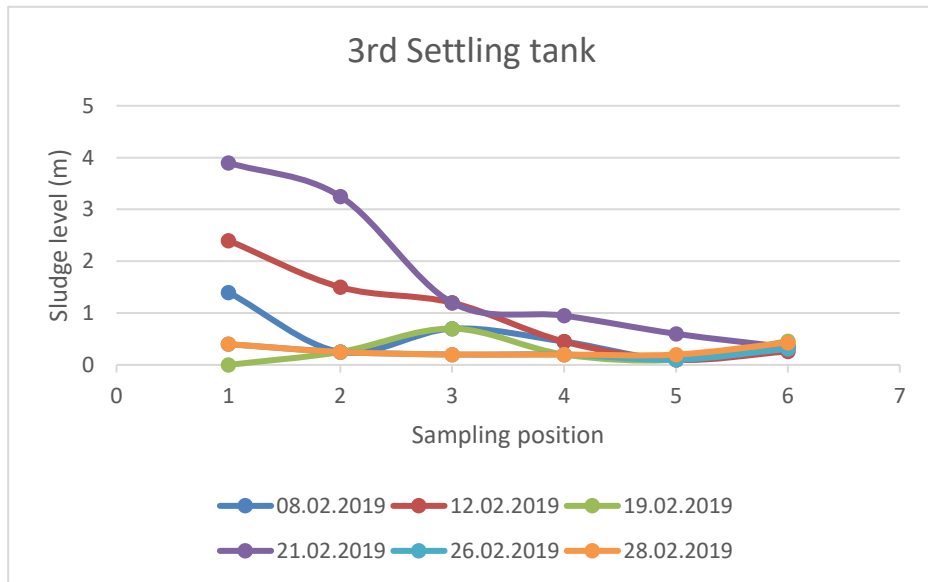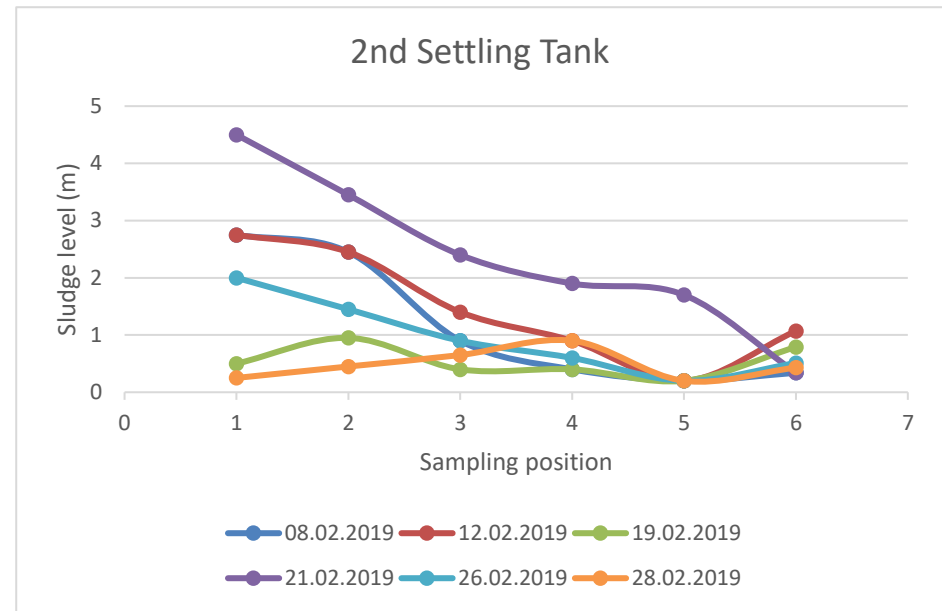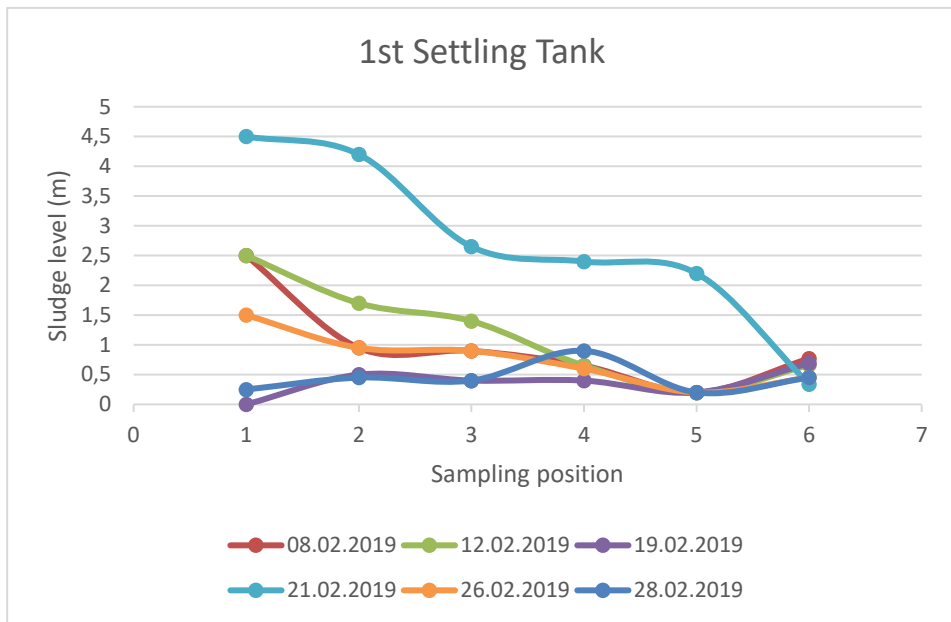
Figure 4.19: Sludge blanket level in settling tank 1, 2, 3 and 4; February 2019. (*6: Online, sludge blanket level shown on the display)
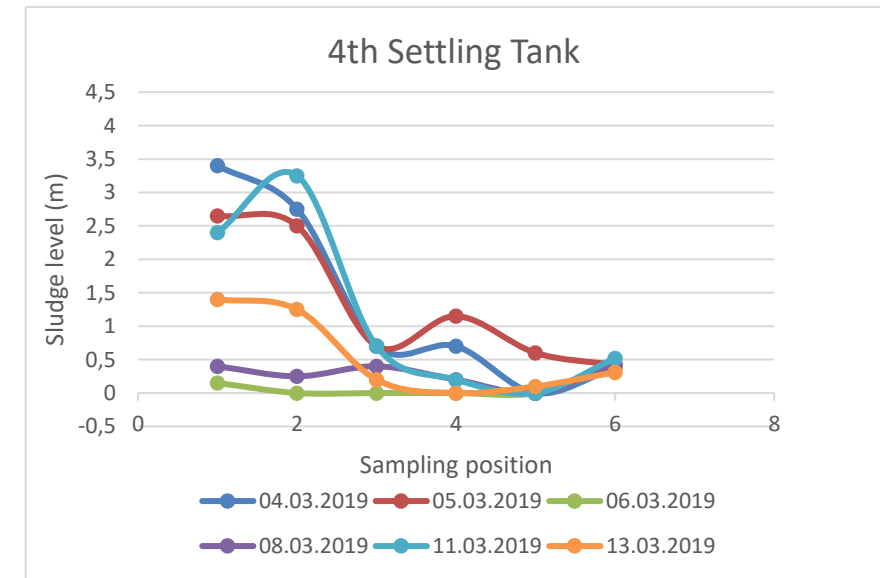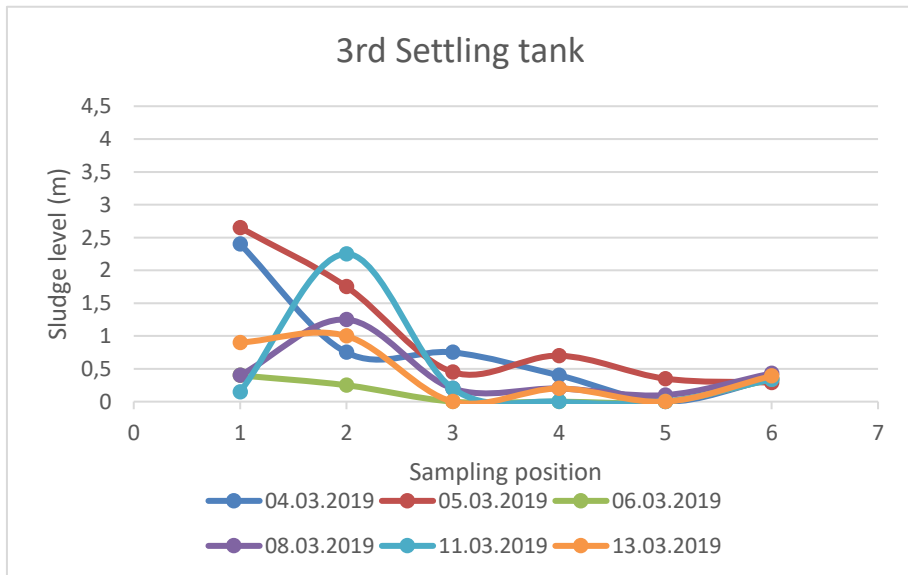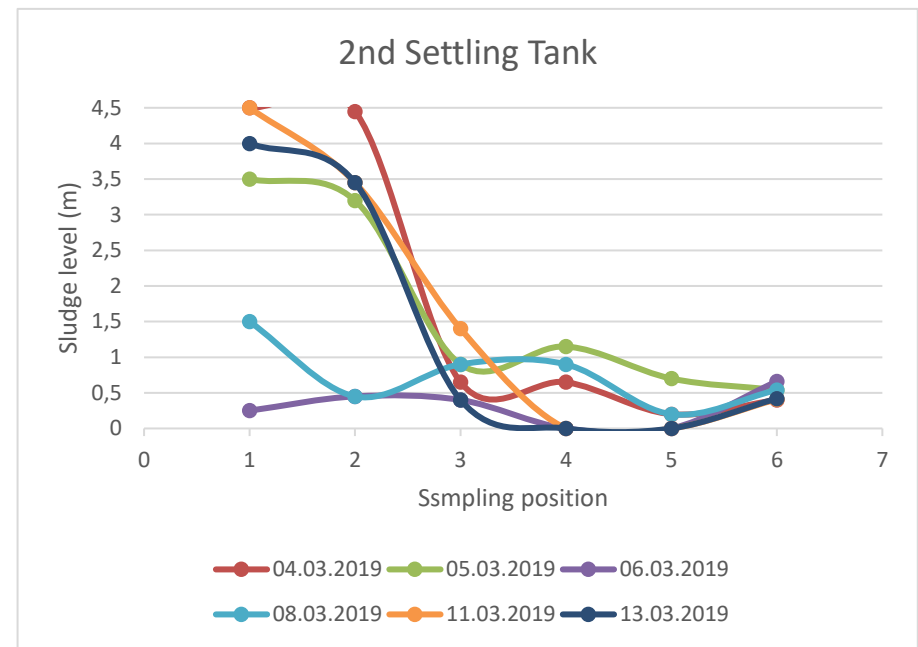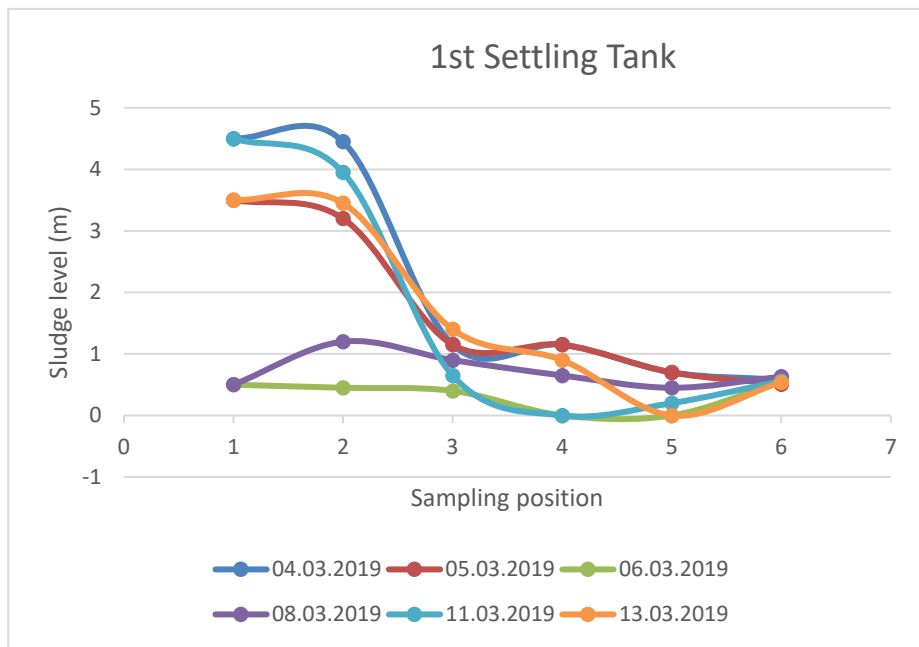
*Figure 4.20: Sludge blanket level in settling tank 1, 2, 3 and 4; March 2019. (*6: Online, sludge blanket level shown on the display)*

4.5 Mass balance in the bioreactor

In this section will review the mass balance in the system. The mass flow through bioreactor and secondary settling tanks was calculated. Figure 4.21 show the concentration on each position.

	Inlet bio	An 1 in	An 2 out	An 3 out	Aer 1 in	Aer 2 out
AVG TSS	166,31	2651,0	1174,6	1282,2	1377,8	1394,7
AVG VSS	151,87	1498,8	959,92	1024,0	1185,2	1164,1
AVG PO4-P	1,30	3,00	2,06	1,82	1,17	1,08
AVG COD	38,50	39,67	58,33	46,50	27,83	31,50
NH4-N	12,7	17,4	14	15,2	14,6	15
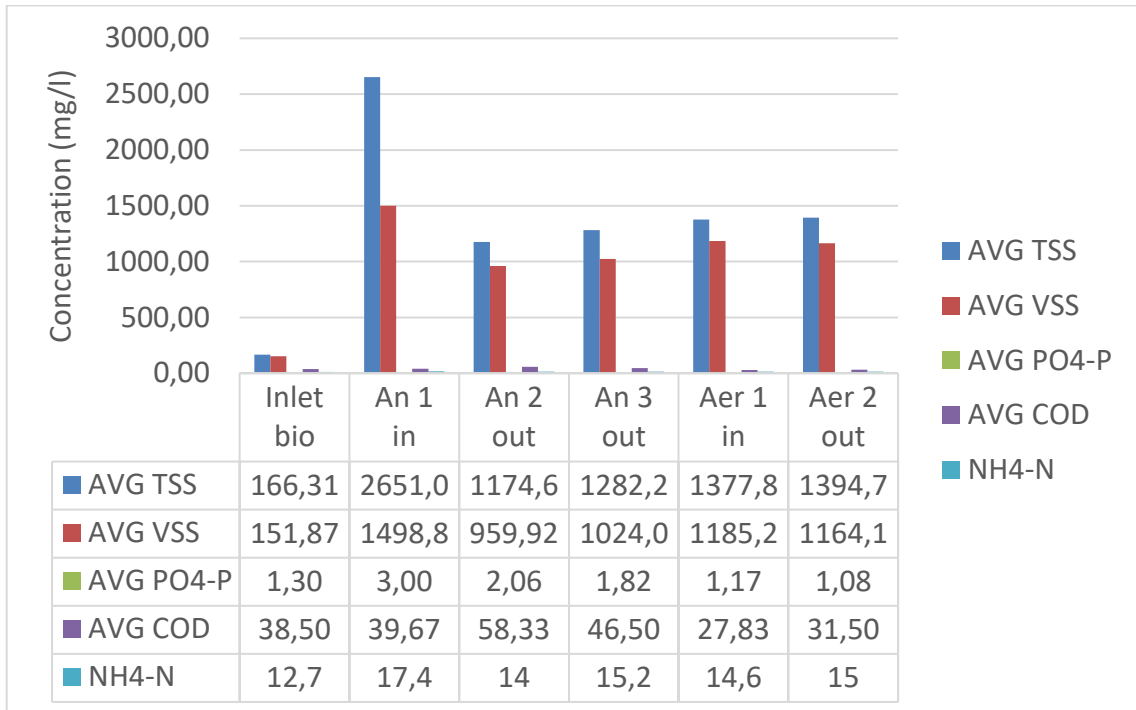
Figure 4.21: Average concentration vs position respectively

Figure 4.21 is a review of mass balance in actual normal operation in SNJ during period January – March 2019. According to Danielsen (2018), IVAR SNJ WWTP operated with 1500- 2000 mg TSS/l in the reactor to maintain sludge age around 4-5 days. To maintain the same sludge age, TSS in the reactors need to achieve approximately 2800 mg TSS/l (Danielsen, 2018). Based on figure 4.21, average TSS from effluent is 1395 mg/l, it means the TSS have less concentration than expected.

Table 4.17: Mass flow through bioreactor line 1

Date	RAS (m³/h)	An 1	An 2	An 3	Aer 1	Aer 2
		(kg TSS h⁻¹)				
22.jan	1050	2415	3568	3366	3844	3536
29.jan	800	4148	3295	3763	4148	4390
19.feb	940	1496	6366	4861	5844	5981
26.feb	800	1794	2917	3612	3786	3851
04.mar	552	1201	2049	2571	3358	3235
11.mar	600	1448	3964	5661	4490	4682

Table 4.17 will present the mass flow through the bioreactor L1. The compartments in the bioreactor are following below equations. These expressions yielded the rate as g TSS h⁻¹, which were converted to kg TSS h⁻¹.

An 1: $Q_{RAS} \times TSS_{RAS} = Q_{RAS} \times TSS_{An1}$

An 2: $(Q_{RAS} \times TSS_{An1}) + (Q_{in} \times TSS_{in}) = (Q_{RAS} + Q_{in}) \times TSS_{An2}$

An 3: $(Q_{RAS} + Q_{in}) \times TSS_{An2} = (Q_{RAS} + Q_{in}) \times TSS_{An3}$

Aer 1: $(Q_{RAS} + Q_{in}) \times TSS_{An2} = (Q_{RAS} + Q_{in}) \times TSS_{Aer1}$

Aer 2: $(Q_{RAS} + Q_{in}) \times TSS_{Aer1} = (Q_{RAS} + Q_{in}) \times TSS_{Aer2}$

4.6   Limitations & Error analysis

This section will review the limitations and accuracy during the experimental, practical work and the source error in the methods and analysis.

As the experimental are done in period January – March. In this period there are much rain and melting snow in Norway, so this period cannot show representative data for whole year. Because the condition of wastewater changes from time to time, and that means it is important to analysis in different weather condition. It has effect on characteristic of wastewater and the effectivity of the EBPR process itself.

Sampling in the bioreactor

During the collection of representative samples from biological process reactor there is a source of error. Any conditions change at the time spent to carry the samples from bioreactor into the process laboratory such as temperature and DO. That is why measurement directly in line is important. Another factor is oxygen in An 3, which means condition are not exactly anaerobic. However, it is not the only one factor that can cause error analysis. Need to review other factors also.

Experimental procedures

The collection of representative samples from biological process is a source of error. During solid analyse, dilution of the samples, homogenous particle distribution and scale could be a source of error.

During titration and because this used manual titration the accuracy is less than if used automatically titration instrument. Low concentration and volume sample could cause the titration to be less accurate. Furthermore, error during titration could occur because of insufficient mixing, some alkalinity was lost due to stripping of CO_2 from the liquid during mixing.

Solid analyse is one of the source errors. The error in the concentrated and mixed representative sample is not completely homogenized prior to analyse and become a high impact on the dilute TSS samples. Also, this TSS samples would have effect into VSS samples.

One important uncertainty during anaerobic batch test was whether it kept anaerobic conditions. During the project, the anaerobic condition in mini reactor was made by an Erlenmeyer and covering with Styrofoam beads on the surface to prevent oxygen entrainment. To make sure it is anaerobic condition, DO was controlled. However, DO measurements was not always representative due to inaccuracy of the oxygen probe at low concentrations.

Analytical procedures

The accuracy measurements of pH and DO. The pH meters accuracy was ± 1% which means appropriate to approximately 0.1 pH unit. The DO measurements, there was some degree and condition uncertainty with the DO concentrations during the project.

Spectrophotometer used for analysis is potentially making errors during the project and associated with the pipetting. Due to used several pipetting per sample, glass cuvettes not rinse prior for analysis PO_4-P, diluted samples analysis are slightly higher inaccuracy compare to analysis used the test kits. Test kits have been used for analysis of COD_{filt} and NH_4-N.

The instrument used for analysis sludge blanket level in settling tank was a source of error due to low accuracy even though support by online data but still cannot use as representative actual data.

5. Conclusion

The aim of this master thesis was to review and investigate the EBPR in IVAR SNJ WWTP process performance. Based on the result of average endogenous and stimulated phosphate release and uptake rates is 1.3 mg P/g VSS h^{-1} at temperature 9-10°C and pH 6-7 respectively. This is in category level ***moderate*** based on the literature values. Furthermore, the influent average ratio of COD_{filt}:PO_4-P is 30 g/g which is referred to as near optimal for EBPR. The treatment efficiency reducing average phosphate concentration in EBPR from influent is 1.3 mg/l to effluent is 1.08 mg/l. Based on data from SNJ, the average treatment efficiency for P removal is 44.9 %.

The primary sludge had a potential for fermentation of COD_{filt} to VFA and suitable for stimulation of phosphate release from the EBPR sludge. As the PO_4-P concentration increase following increasing volume VFA added. This indicate the sludge is good and potential for process EBPR.

The batch test indicated behaviour of the biological process as expected, PO_4-P released in anaerobic condition and uptake in aerobic condition and achieved close to zero after 3 hours anaerobic, and between 3 hours and 20 hours aerobic. This indicate that the sludge has potential of high PO_4-P removal if the conditions are optimal. In the measurement of the full-scale plant (L1) the PO_4-P removal was less due to release of PO_4-P in the settling tanks as a result of long retention time of the sludge and anaerobic conditions.

Measurements in the settling tanks show on high sludge blanket level. Even though the SVI is low at 90.4 mg/l, which indicate good settling of the activated sludge and high-quality effluent compared to literatures values. The high sludge blanket was thus caused of other factors such as hydraulic conditions and possible the sludge scrapers. Also, the results indicated that the settling tanks produced secondary phosphate release and thus reducing the overall EBPR process performance.

6. Recommendations

Based on the results from this project, there are still need for optimization of the EBPR process at SNJ . Suggestions for further studies are:

- The oxygen concentration in the anaerobic tanks have to be minimized. The possibility of avoiding dissolved oxygen in the influent should be investigated.
- Investigate the benefit and optimization of fermentation products on P removal in sequencing batch reactor configuration, for an operation scheme which only favours PAO.
- Analysis of other cations such as Ca, K, and Mg can be included in the next project to see effect on phosphorus removal.
- The removal of sludge in settling tanks should be improved to avoid secondary release and elevated phosphate concentration in the effluent.
- Need to investigate and do further experiment to improve mass balance in the system.
- If the EBPR activity is considerable stable, phosphate release tests should be performed on waste sludge and in the activated sludge to determine if any difference between them.

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APPENDIX

A. Sampling position
    1. At SNJ WWTP
       Figure A and table A are presents the positions where samples collected
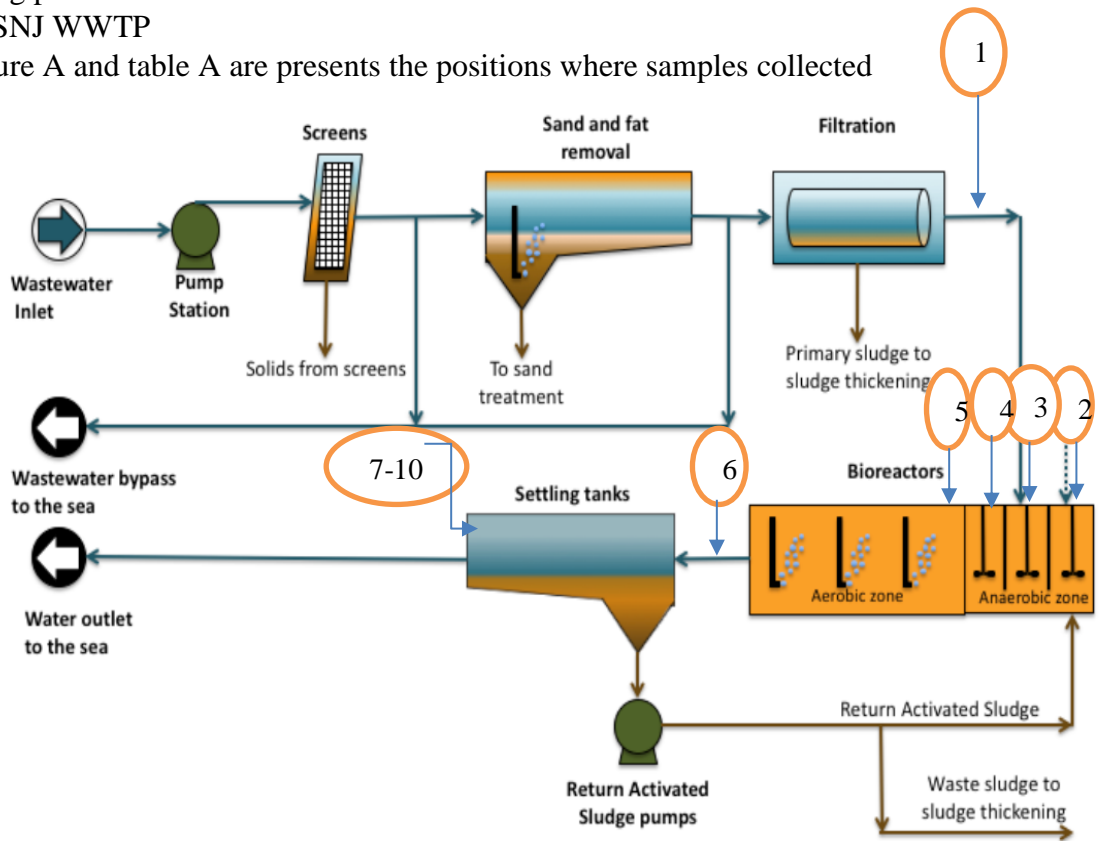
Figure A: Sample points collected

Table A: Sample point descriptions

Position	Description	Stream type
1	Inlet bioreactor	Wastewater
2	Anaerobic chamber 1 (An 1)	Activated sludge
3	Anaerobic chamber 2 (An 2)	MLSS
4	Anaerobic chamber 3 (An 3)	MLSS
5	Aerobic zone (Aer 1)	MLSS
6	Aerobic 2 (Aer 2)	MLSS
7-10	Settling Tanks (1-4)	Treated wastewater

B. Weekly characterization in EBPR Line 1

DATE	SAMPLE No.	POSITION	FLOW m3/h	DO mg/L	COND mS/cm	pH	Temp °C	TSS mg/L	VSS mg/L	PO_4-P mg/L	COD_{filt} mg/L	C:P g/g	NH_4^+ mg/L	C:N g/g
22.jan	1	Inlet bio	2682	1,40	2,56	7,18	12,6	192,2	n.a	1,49	41	27,52	n.a	n.a
	2	An 1 in	1050	0,38	2,42	6,40	11,3	2300	n.a	2,52	26	10,32	n.a	n.a
	3	An 2 out	3732	0,34	2,6	6,57	11,6	956	n.a	1,9	68	35,79	n.a	n.a
	4	An 3 out	3732	0,25	2,45	6,66	11,1	902	n.a	2,02	75	37,13	n.a	n.a
	5	Aer 1 in	3732	1,42	2,47	6,82	11,5	1030	n.a	1,2	25	20,83	n.a	n.a
	6	Aer 2 out	3732	1,64	2,52	6,93	11,3	947,5	n.a	0,74	38	51,35	n.a	n.a
	7	Sed 1	3732	n.a	2,94	6,65	14,5	25	n.a	1,3	56	43,08	n.a	n.a
	8	Sed 2	3732	n.a	2,63	6,54	13,3	37	n.a	1,36	18	13,24	n.a	n.a
	9	Sed 3	3732	n.a	2,84	7,32	13,2	34	n.a	1,34	19	14,18	n.a	n.a
	10	Sed 4	3732	n.a	2,62	7,46	12,7	24	n.a	1,26	16	12,70	n.a	n.a
	11	Waste sludge	1050	0,89	2,72	6,92	13,4	TS: 0,17	n.a	1,22	86	70,49	16,8	5,12
	12	Filter sludge	1050	0,54	2,58	6,88	12,2	TS: 0,7	n.a	2,55	124	48,63	19,9	6,23
29.jan	1	Inlet bio	1440	1,42	3,82	7,52	12,6	208	n.a	1,59	45	28,30	n.a	n.a
	2	An 1 in	800	0,40	3,26	7,22	11,8	5185	n.a	3,26	24	7,36	n.a	n.a
	3	An 2 out	2240	0,38	4,83	7,22	11,5	1471	n.a	2,58	150	58,14	n.a	n.a
	4	An 3 out	2240	0,45	3,85	7,20	12,3	1680	n.a	1,76	80	45,45	n.a	n.a
	5	Aer 1 in	2240	0,46	3,45	7,49	11,8	1852	n.a	0,94	22	23,40	n.a	n.a
	6	Aer 2 out	2240	0,42	3,28	7,65	12,5	1960	n.a	1,02	20	19,61	n.a	n.a
	7	Sed 1	2240	6,10	3,05	7,45	13,5	29	n.a	1,38	19	13,77	n.a	n.a
	8	Sed 2	2240	5,87	3,07	7,42	13,3	50	n.a	1,40	21	15,00	n.a	n.a
	9	Sed 3	2240	6,18	3,09	7,44	13,2	20	n.a	1,54	16	10,39	n.a	n.a
	10	Sed 4	2240	6,24	3,08	7,60	13,3	24	n.a	1,42	21	14,79	n.a	n.a

DATE	SAMPLE	POSITION	FLOW	DO	COND	pH	Temp	TSS	VSS	PO_4-P	COD_{filt}	C:P	NH_4^+	C:N
	No.		m3/h	mg/L	mS/cm		°C	mg/L	mg/L	mg/L	mg/L	g/g	mg/L	g/g
04.feb	1	Inlet bio	2628	1,12	3,45	6,89	9,7	114,29	n.a	1,7	43	25,29	n.a	n.a
	2	An 1 in	1200	0,37	3,35	6,90	9,5	2020,6	n.a	4,2	35	8,33	n.a	n.a
	3	An 2 out	3828	0,34	3,61	7,16	9,3	897,96	n.a	2,6	29	11,15	n.a	n.a
	4	An 3 out	3828	0,36	3,59	7,16	9,3	891,67	n.a	2,6	24	9,23	n.a	n.a
	5	Aer 1 in	3828	0,33	3,57	7,06	9,6	1293,9	n.a	2,1	28	13,33	n.a	n.a
	6	Aer 2 out	3828	0,33	3,59	7,13	9,6	1342,2	n.a	1,1	22	20	n.a	n.a
	7	Sed 1	3828	n.a	n.a	6,93	10,1	15	n.a	2,4	44	18,33	n.a	n.a
	8	Sed 2	3828	n.a	n.a	7,23	10,2	13	n.a	2,76	48	17,39	n.a	n.a
	9	Sed 3	3828	n.a	n.a	7,45	10,1	18	n.a	1,98	37	18,69	n.a	n.a
	10	Sed 4	3828	n.a	n.a	7,57	10,1	12	n.a	2,52	35	13,89	n.a	n.a
	11	Waste sludge				7,77	11,2	0	n.a	2,2		0		
	12	Filter sludge				7,72	11,5	TS: 1,49	n.a	3,8		0		
19.feb	1	Inlet bio	2736	6,52	3,40	7,39	10,50	70,20	10,6	1	34	34,00	n.a	n.a
	2	An 1 in	940	0,43	2,86	7,12	10,40	1591,11	286,7	2,1	40	19,05	n.a	n.a
	3	An 2 out	3676	0,45	2,81	7,09	9,70	1731,82	400,0	1,85	41	22,16	n.a	n.a
	4	An 3 out	3676	0,58	2,40	7,04	9,90	1322,45	191,8	1,35	28	20,74	n.a	n.a
	5	Aer 1 in	3676	2,72	2,14	7,08	10,00	1589,80	289,8	0,9	37	41,11	n.a	n.a
	6	Aer 2 out	3676	3,34	2,15	7,19	10,00	1627,08	345,8	0,6	30	50,00	n.a	n.a
	7	Sed 1	3676	5,69	2,12	7,34	10,00	54,77	n.a	1,4	51	36,43	n.a	n.a
	8	Sed 2	3676	5,42	2,12	7,08	10,00	34,00	n.a	1,6	52	32,50	n.a	n.a
	9	Sed 3	3676	5,39	2,19	7,42	10,10	36,50	n.a	1,5	49	32,67	n.a	n.a
	10	Sed 4	3676	5,57	2,14	7,19	10,10	34,67	n.a	1,5	51	34,00	n.a	n.a
	11	Waste sludge		n.a	3,12	7,02		TS: 0,57		2,1	83	39,52	n.a	n.a
18.feb	12	Filter sludge		n.a	3,20	6,79		TS: 1,2		2,5	118	47,20	n.a	n.a

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DATE	SAMPLE No.	POSITION	FLOW m3/h	DO mg/L	COND mS/cm	pH	Temp °C	TSS mg/L	VSS mg/L	PO$_4$-P mg/L	COD$_{filt}$ mg/L	C:P g/g	NH$_4^+$ mg/L	C:N g/g
26.feb	1	Inlet bio	1656	6,52	3,4	7,39	10,5	226	21	1,4	32	22,86	n.a	n.a
	2	An 1 in	800	0,43	2,86	7,12	10,4	2242,6	961,7	4	38	9,50	n.a	n.a
	3	An 2 out	2456	0,45	2,81	7,09	9,7	1187,5	200	2,9	40	13,79	n.a	n.a
	4	An 3 out	2456	0,58	2,4	7,04	9,9	1470,8	237,5	2,4	29	12,08	n.a	n.a
	5	Aer 1 in	2456	2,72	2,14	7,08	10	1541,7	237,5	1,8	22	12,22	n.a	n.a
	6	Aer 2 out	2456	3,34	2,15	7,19	10	1568	254,17	2	31	15,50	n.a	n.a
	7	Sed 1	2456	5,69	2,12	7,34	10	17,09	n.a	2,1	31	14,76	n.a	n.a
	8	Sed 2	2456	5,42	2,12	7,08	10	14,5	n.a	2,2	31	14,09	n.a	n.a
	9	Sed 3	2456	5,39	2,19	7,42	10,1	13,13	n.a	2,1	37	17,62	n.a	n.a
	10	Sed 4	2456	5,57	2,14	7,19	10,1	13,5	n.a	2,1	31	14,76	n.a	n.a
	11	Waste sludge			n.a	n.a	n.a	n.a	n.a				n.a	n.a
25.feb	12	Filter sludge			3	6,91	n.a	TS: 1.30	0,24				n.a	n.a
28.feb	1	Inlet 67oil treatment	1260	5,29	3,55	7,59	9,70	49,24	6,09	1,60	28,00	17,50	n.a	n.a
	2	An 1 in	220	0,15	3,04	7,39	9,80	3130,44	495,65	5,40	49,00	9,07	n.a	n.a
	3	An 2 out	1480	0,28	3,30	7,37	9,60	1462,50	225,00	3,10	26,00	8,39	n.a	n.a
	4	An 3 out	1480	0,33	2,94	7,33	9,90	1375,00	208,33	2,30	25,00	10,87	n.a	n.a
	5	Aer 1 in	1480	2,51	2,61	7,36	10,10	1387,50	262,50	1,50	27,00	18,00	n.a	n.a
	6	Aer 2 out	1480	2,58	2,76	7,37	10,10	1408,16	232,65	1,30	21,00	16,15	n.a	n.a

DATE	SAMPLE	POSITION	FLOW	DO	COND	pH	Temp	TSS	VSS	PO4-P	CODfilt	C:P	NH4+	C:N
	No.		m3/h	mg/L	mS/cm		C	mg/L	mg/L	mg/L		mg/L	mg/L	mg/L
	7	Sed 1	1480	5,56	2,76	7,38	10,20	18,00	n.a	2,30	29,00	12,61	n.a	n.a
	8	Sed 2	1480	5,52	2,76	7,29	10,20	14,00	n.a	2,20	32,00	14,55	n.a	n.a
	9	Sed 3	1480	5,54	2,79	7,31	10,20	16,58	n.a	2,20	37,00	16,82	n.a	n.a
	10	Sed 4	1480	5,12	2,76	7,17	10,10	18,00	n.a	2,20	32,00	14,55	n.a	n.a
	11	Waste sludge												
	12	Filter sludge												
04.mar	1	Inlet 68oil treatment	2628	7,49	8,15	7,56	9,20	215,00	n.a	1,30	37,00	28,46	n.a	n.a
	2	An 1 in	552	0,33	6,78	7,26	9,30	2175,00	n.a	3,20	55,00	17,19	n.a	n.a
	3	An 2 out	3180	0,36	7,70	7,26	8,90	644,44	n.a	1,50	20,00	13,33	n.a	n.a
	4	An 3 out	3180	0,37	7,44	7,29	8,90	808,33	n.a	1,60	29,00	18,13	n.a	n.a
	5	Aer 1 in	3180	1,38	7,31	7,17	9,30	1056,00	n.a	1,30	27,00	20,77	n.a	n.a
	6	Aer 2 out	3180	3,79	7,30	7,17	9,30	1017,39	n.a	1,30	37,00	28,46	n.a	n.a
	7	Sed 1	3180	5,44	6,76	7,27	9,50	48,00	n.a	1,50	30,00	20,00	n.a	n.a
	8	Sed 2	3180	5,52	6,81	7,15	9,50	40,50	n.a	1,40	30,00	21,43	n.a	n.a
	9	Sed 3	3180	5,82	6,41	7,32	9,50	23,00	n.a	1,70	28,00	16,47	n.a	n.a
	10	Sed 4	3180	5,67	6,60	7,13	9,50	42,57	n.a	1,50	21,00	14,00	n.a	n.a
	11	Waste sludge	3180	n.a	6,99	7,04	10,40	TS: 0,5	n.a	n.a	n.a	n.a	n.a	n.a
	12	Filter sludge	3180	n.a	6,82	7,28	10,20	TS: 1,38	n.a	n.a	n.a	n.a	n.a	n.a

DATE	SAMPLE	POSITION	FLOW	DO	COND	pH	Temp	TSS	VSS	PO$_4$-P	COD$_{filt}$	C:P	NH$_4^+$	C:N
	No.		m3/h	mg/L	mS/cm		°C	mg/L	mg/L	mg/L	mg/L	g/g	mg/L	g/g
7.Mar	1	Inlet bio	2700	7,42	2,47	7,84	9,20	211	187	1,30	24,00	19,00	n.a	n.a
	2	An 1 in	600	0,33	2,88	7,64	9,10	1950,00	263,64	2,70	27,00	10,00	n.a	n.a
	3	An 2 out	3300	0,34	2,61	7,48	8,80	852,00	84,00	1,70	21,00	12,35	n.a	n.a
	4	An 3 out	3300	0,36	2,77	7,24	8,90	956,00	100,00	1,80	20,00	11,11	n.a	n.a
	5	Aer 1 in	3300	1,64	2,98	7,65	9,10	1091,30	104,35	1,30	19,00	14,62	n.a	n.a
	6	Aer 2 out	3300	2,74	3,03	7,84	9,20	1052,00	120,00	1,20	22,00	18,33	n.a	n.a
	7	Sed 1	3300	5,24	3,24	7,57	9,80	27,00	n.a	1,50	28,00	18,67	n.a	n.a
	8	Sed 2	3300	5,46	3,28	7,36	9,50	22,61	n.a	1,60	27,00	16,88	n.a	n.a
	9	Sed 3	3300	5,47	3,36	7,66	9,70	21,00	n.a	1,70	32,00	18,82	n.a	n.a
	10	Sed 4	3300	5,31	3,32	7,48	9,50	18,50	n.a	1,70	25,00	14,71	n.a	n.a
	11	Waste sludge		n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
	12	Filter sludge		n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
11.mar	1	Inlet biol treatment	3150	4.15	4,05	6,74	8,90	86,46	11,46	1,00	42,00	42,00	12,70	3,31
	2	An 1 in	600	0,21	4,31	6,96	9,20	2412,77	561,70	2,90	55,00	18,97	17,40	3,16
	3	An 2 out	3750	0,52	4,38	6,96	9,00	1057,14	163,27	1,60	31,00	19,38	14,00	2,21
	4	An 3 out	3750	0,83	4,56	6,98	9,00	1509,68	264,52	1,80	38,00	21,11	15,20	2,50
	5	Aer 1 in	3750	1,55	4,55	7,17	9,10	1197,30	281,08	0,90	34,00	37,78	14,60	2,33
	6	Aer 2 out	3750	1,62	4,55	7,23	9,10	1248,49	200,00	0,80	33,00	41,25	15,00	2,20
	7	Sed 1	3750	n.a	3,74	7,45	9,20	15,50	n.a	1,30	38,00	29,23	18,40	2,07
	8	Sed 2	3750	n.a	3,80	7,19	9,10	17,28	n.a	1,30	37,00	28,46	17,40	2,13
	9	Sed 3	3750	n.a	3,67	7,64	9,20	20,10	n.a	1,20	35,00	29,17	18,50	1,89
	10	Sed 4	3750	n.a	3,69	7,32	9,10	19,00	n.a	1,20	31,00	25,83	18,20	1,70

DATE	SAMPLE No.	POSITION	FLOW m3/h	DO mg/L	COND mS/cm	pH	Temp °C	TSS mg/L	VSS mg/L	PO_4-P mg/L	COD_{filt} mg/L	C:P g/g	NH_4^+ mg/L	C:N g/g
	12	Filter sludge		n.a	4,03	7,12	11,20	TS: 1,79	n.a	1,60	n.a	n.a	13,40	n.a
13.mar	1	Inlet biol treatment	3050	9,65	5,50	7,28	8,20	50,51	14,14	0,50	20,00	40,00	n.a	n.a
	2	An 1 in	620	0,00	3,65	7,11	8,20	2609,09	495,45	2,30	28,00	12,17	n.a	n.a
	3	An 2 out	3670	5,67	5,08	7,14	7,90	661,22	97,96	0,80	23,00	28,75	n.a	n.a
	4	An 3 out	3670	0,36	4,73	7,24	7,90	633,33	87,50	0,80	21,00	26,25	n.a	n.a
	5	Aer 1 in	3670	2,43	3,59	7,32	8,10	840,82	159,18	0,60	21,00	35,00	n.a	n.a
	6	Aer 2 out	3670	2,20	3,22	7,37	8,10	916,00	140,00	0,50	26,00	52,00	n.a	n.a
	7	Sed 1	3670	0,00	2,39	7,36	8,30	26,63	n.a	1,20	27,00	22,50	n.a	n.a
	8	Sed 2	3670	0,00	2,46	6,90	8,20	46,00	n.a	1,20	28,00	23,33	n.a	n.a
	9	Sed 3	3670	0,00	2,66	7,17	8,50	16,50	n.a	1,60	27,00	16,88	n.a	n.a
	10	Sed 4	3670	0,00	2,58	7,17	8,40	17,68	n.a	1,20	21,00	17,50	n.a	n.a
	11	Waste sludge	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
	12	Filter sludge	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a

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C. Phosphate release and uptake in bioreactor & batch test

1. Calculation of phosphate release and uptake rates from bioreactor.
   The rate expression for each section is presented as below formulas. These formulas yielded the rates as g P/g VSS h^{-1}, which were converted to mg P /g VSS h^{-1}

$$rate_{An\ 1} = \frac{Q_{RAS}(P_{An\ 1} - P_{RAS})}{V_{An\ 1}VSS_{An\ 1}}$$

$$rate_{An\ 2} = \frac{[(Q_{RAS} + Q_{Inlet})P_{An\ 2}] - [(Q_{RAS}P_{RAS}) + (Q_{Inlet}P_{Inlet})]}{V_{An\ 2}VSS_{An\ 2}}$$

$$rate_{An\ 3} = \frac{(Q_{RAS} + Q_{Inlet})(P_{An\ 3} - P_{An\ 2})}{V_{An\ 3}VSS_{An\ 3}}$$

$$rate_{Aer\ 1} = \frac{(Q_{RAS} + Q_{Inlet})(P_{Aer\ 1} - P_{An\ 3})}{V_{Aer\ 1}VSS_{Aer\ 1}}$$

$$rate_{An\ 3} = \frac{(Q_{RAS} + Q_{Inlet})(P_{Aer\ 2} - P_{Aer\ 1})}{V_{Aer\ 2}VSS_{Aer\ 2}}$$

Date	Position	mg P/g VSS h^{-1} (release)	mg P/g VSS h^{-1} (uptake))
19.02	An 1	0.004	
	An 2	6800.589	
	An 3		-0.010
	Aer 1		-0.006
	Aer 2		-0.003
26.02	An 1	0.004	
	An 2	7122.381	
	An 3		-0.005
	Aer 1		-0.007
	Aer 2		-0.002
07.11	An 1	0.002	
	An 2	5609.939	
	An 3	0.003	
	Aer 1		-0.017
	Aer 2		-0.003
11.11	An 1	0.001	
	An 2	5999.971	
	An 3	0.003	
	Aer 1		-0.013
	Aer 2		-0.002

2. Phosphate release and uptake in batch experiment

DATE	TIME	PO$_4$-P (mg/L)
13.feb	09:00	1,8
	10:00	1,9
	11:00	3,7
(Aerob)	12:00	3,4
	13:00	0,2
	14:00	0,1
	15:00	0,1
20.feb		1,8
20.feb	09:00	1,6
CONCENTRATED	10:00	2,2
	11:00	3,6
(Aerob)	12:00	3
	13:00	0,5
	14:00	0,1
	15:00	0,01
20.feb	09:00	2,7
CONCENTRATED	10:00	3,7
	11:00	5,6
(Aerob)	12:00	5,7
	13:00	0,7
	14:00	0,1
	15:00	0,03
20.feb	09:00	3,4
CONCENTRATED	10:00	4,8
	11:00	5,9
(Aerob)	12:00	5
	13:00	1
	14:00	0,7
	15:00	0,5

DATE	TIME	PO$_4$-P (mg/L)
27.feb		1,5
27.feb	09:00	1,1
UNCONCENTRATED	10:00	1,3
	11:00	1,7
(Aerob)	12:00	1,5
	13:00	1
	14:00	0,8
	15:00	0,67
27.feb	09:00	3,7
UNCONCENTRATED	10:00	3,2
30	11:00	3,5
(Aerob)	12:00	3,9
	13:00	2,4
	14:00	1,8
	15:00	1,8
27.feb		
UNCONCENTRATED	09:00	2,7
50	10:00	4,2
(Aerob)	11:00	4,6
	12:00	3
	13:00	3,2
	14:00	2,7
	15:00	2,7

DATE	TIME	PO4-P (mg/L)
06.mar	08:00	1,7
06.mar		
UNCONCENTRATED	09:00	1,2
	10:00	1,3
(Aerob)	11:00	1,5
	12:00	1,2
	13:00	0,8
	14:00	0,6
	15:00	0,6
07.mar	16:00	0,4
	08:00	0,1
06.mar		
UNCONCENTRATED	09:00	2,6
30	10:00	2,9
(Aerob)	11:00	3,1
	12:00	2,8
	13:00	1,6
	14:00	1,3
	15:00	1,1
07.mar	16:00	1,1
	08:00	0,9
06.mar		
UNCONCENTRATED	09:00	3,7
50	10:00	3,8
(Aerob)	11:00	4
	12:00	3,2
	13:00	2,6
	14:00	2,1
	15:00	1,9
07.mar	16:00	1,7
	08:00	0,9

D. Sludge blanket level in settling tanks

Sed. Tank No.	Sed 1						Sed 2						Sed 3						Sed 4					
Depth (m)	4,5	4,5	4,4	4,4	4,2		4,5	4,5	4,4	4,4	4,2		4,4	4,3	4,2	4,2	4,1		4,4	4,3	4,2	4,2	4,1	
Date	1	2	3	4	5	On-line	1	2	3	4	5	On-line	1	2	3	4	5	On-line	1	2	3	4	5	On-line
January																								
14.01.2019	4,5	3,7	2,4	2,4	1,7	0,34	3,5	2,95	2,9	2,4	1,7	1	3,9	3,25	2,2	1,2	1,1	0,69	0,4	2,75	1,7	0,7	0,1	0,94
16.01.2019	4,25	3,95	2,65	1,65	1,2	0,47	4,25	4,2	2,4	1,65	1,2	1,38	3,65	2,5	1,2	0,95	0,85	0,34	3,9	2,75	1,45	1,2	1,1	0,84
21.01.2019	4,25	3,95	1,9	1,4	0,9	0,53	4,5	3,95	2,4	1,4	0,7	0,53	3,9	3,5	0,95	0,95	0,6	0,57	4,15	3,75	1,25	1,25	0,85	0,39
22.01.2019	3	3,45	2,4	1,4	0,7	0,59	4,25	3,95	2,15	1,4	0,7	0,53	3,9	3,5	0,95	0,95	0,6	0,57	4,15	3,75	1,2	1,2	0,85	0,39
23.01.2019	4	2,7	1,9	1,15	0,2	0,72	3	2,95	1,4	1,4	0,2	0,89	4,15	3,25	1,7	0,7	0,6	0,51	4,4	3,75	1,2	0,95	0,6	0,44
24.01.2019	4	3,45	2,4	1,65	1,2	0,6	4	3,45	2,4	1,9	1,2	0,77	3,9	2,75	1,95	1,45	1,1	0,53	3,4	2,75	1,7	1,2	1,1	0,37
30.01.2019	2,5	1,95	1,4	0,9	0,7	0,57	2,5	1,95	1,4	0,9	0,7	1,05	1,4	0,75	0,2	0	0	0,4	1,4	1,25	0,45	0,2	0	0,49
February																								
08.02.2019	2,5	0,95	0,9	0,65	0,2	0,77	2,75	2,45	0,9	0,4	0,2	0,34	1,4	0,25	0,7	0,45	0,1	0,37	1,9	1,75	0,7	0,2	0,1	0,57
12.02.2019	2,5	1,7	1,4	0,65	0,2	0,66	2,75	2,45	1,4	0,9	0,2	1,07	2,4	1,5	1,2	0,45	0,1	0,26	3,4	2,5	1,7	1,2	0,1	0,34

Date																							
19.02.2019	0	0,5	0,4	0,4	0,2	*0,69*	0,5	0,95	0,4	0,4	0,2	*0,79*	0	0,25	0,7	0,2	0,1	*0,46*	0	0,25	0,2	0,2	0,1	*0,59*
21.02.2019	4,5	4,2	2,65	2,4	2,2	*0,34*	4,5	3,45	2,4	1,9	1,7	*0,34*	3,9	3,25	1,2	0,95	0,6	*0,34*	3,4	3,25	1,7	1,2	0,6	*0,31*
26.02.2019	1,5	0,95	0,9	0,6	0,2	*0,45*	2	1,45	0,9	0,6	0,2	*0,51*	0,4	0,25	0,2	0,2	0,1	*0,31*	0,4	0,45	0,45	0,45	0,1	*0,25*
28.02.2019	0,25	0,45	0,4	0,9	0,2	*0,45*	0,25	0,45	0,65	0,9	0,2	*0,43*	0,4	0,25	0,2	0,2	0,2	*0,43*	0,4	0,25	0,2	0,2	0	*0,27*
MarchH																								
04.03.2019	4,5	4,45	1,15	1,15	0,7	*0,58*	4,5	4,45	0,65	0,65	0,2	*0,4*	2,4	0,75	0,75	0,4	0	*0,35*	3,4	2,75	0,7	0,7	0	*0,38*
05.03.2019	3,5	3,2	1,15	1,15	0,7	*0,51*	3,5	3,2	0,9	1,15	0,7	*0,54*	2,65	1,75	0,45	0,7	0,35	*0,29*	2,65	2,5	0,7	1,15	0,6	*0,42*
06.03.2019	0,5	0,45	0,4	0	0	*0,55*	0,25	0,45	0,4	0	0	*0,66*	0,4	0,25	0	0	0	*0,34*	0,15	0	0	0	0	*0,4*
08.03.2019	0,5	1,2	0,9	0,65	0,45	*0,63*	1,5	0,45	0,9	0,9	0,2	*0,54*	0,4	1,25	0,2	0,2	0,1	*0,43*	0,4	0,25	0,4	0,2	0	*0,43*
11.03.2019	4,5	3,95	0,65	0	0,2	*0,56*	4,5	3,45	1,4	0	0	*0,41*	0,15	2,25	0,2	0	0	*0,34*	2,4	3,25	0,7	0,2	0	*0,52*
13.03.2019	3,5	3,45	1,4	0,9	0	*0,54*	4	3,45	0,4	0	0	*0,42*	0,9	1	0	0,2	0	*0,39*	1,4	1,25	0,2	0	0,1	*0,31*