Master's thesis

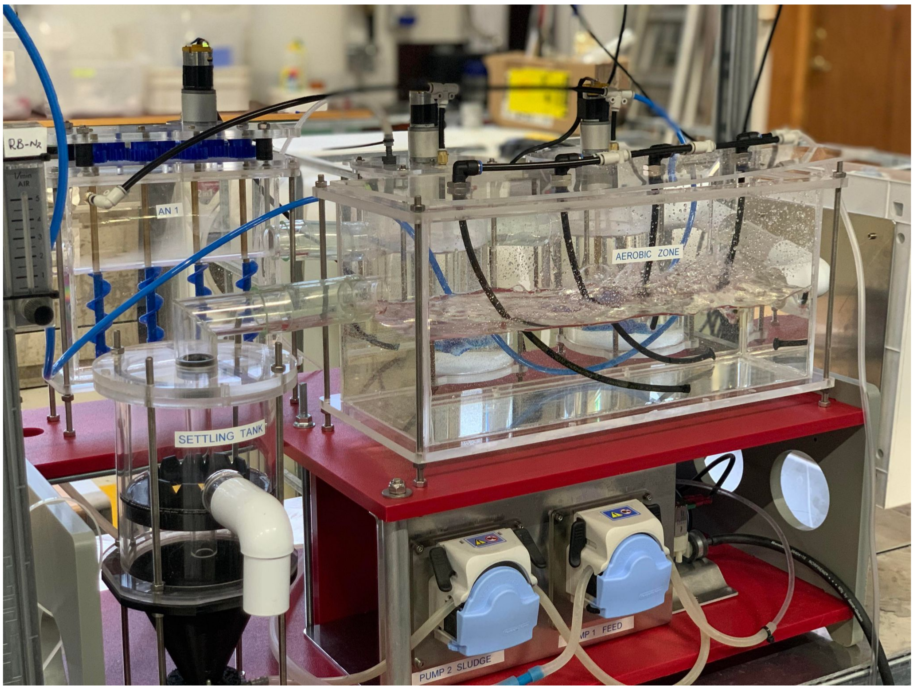
NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Viktoria Røvig

Startup of Lab-Scaled pilot for EBPR

Work package 1 - WIDER UPTAKE

Master's thesis in Civil and Environmental Engineering
Supervisor: Stein Woll Østerhus
Co-supervisor: Blanca Magdalena Gonzalez Silva
July 2022



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Abstract

IVAR Sentralrenseanlegg Nord – Jæren (SNJ) is a wastewater treatment plant that treats the wastewater form the Nord – Jæren region in Norway. The treatment plant is designed with Enhanced Biological Phosphorous Removal (EBPR) and wants to use wastewater as a renewable resource to produce biogas and fertilizer. When treating the wastewater, they have discovered some challenges connected to achieving the desired P – removal. A lab – scaled pilot in scale 1:100 of the secondary treatment process at IVAR is built in order to optimize the treatment process. This thesis is focused around the startup of the lab – scaled pilot and making the pilot operate with similar operational parameters as used at IVAR. It was investigated whether the lab – scaled pilot was able to perform phosphorous removal without experiencing problems due to its small scale. When the pilot reached steady conditions for operation it was able to remove an average of 42 % PO_4–P with a maximum removal of 69 %. The operational challenges that occurred in the project work seem to be related to temperature. Further work needs to focus on reducing the temperature in the wastewater to be similar to what is found at IVAR. This may reduce operational challenges while providing a better foundation for optimizing phosphorus removal.

Sammendrag

IVAR Sentralrenseanlegg Nord – Jæren (SNJ) er et avløpsrenseanlegg som renser avløpsvannet fra regionen Nord – Jæren i Norge. Anlegget er designet med forbedret biologisk fjerning av fosfor (EBPR) ettersom de ønsker å bruke avløpsvannet som en fornybar resurs til å produsere biogass og gjødsel. De har opplevd noen utfordringer ved renseprosessen i forbindelse med å oppnå ønsket fosforfjerning. En labskala pilot i størrelse 1:100 av sekundærrenseprosessen til IVAR er bygget for å optimalisere prosessen. Denne oppgaven fokuserer på oppstarten av den labskalerte piloten og arbeidet med å oppnå lignende driftsparametere som benyttet hos IVAR. Det ble undersøkt om den labskalerte piloten klarte å utføre fosfor fjerning uten å få problemer på grunn av den lille størrelsen. Da piloten oppnådde stabile driftsforhold var den i stand til å fjerne et gjennomsnitt på 42 % PO_4–P med en maksimal fjerning på 69 %. Utfjordinger knyttet til driften av piloten virker til å være temperatur relatert. Videre arbeid må fokusere på reduksjon av temperaturen på avløpsvannet for å nå samme temperaturer som hos IVAR. Det vil trolig redusere driftsutfjordinger og legge et bedre grunnlag for optimalisering av fosforfjerning.

Abbreviation

BOD	–	Biological Oxygen Demand
C	–	Carbon
COD	–	Chemical Oxygen Demand
DPAOs	–	Denitrifying PAOs
EBPR	–	Enhanced Biological Phosphorus Removal
GAOs	–	Glycogen Accumulating Organisms
HRT	–	Hydraulic Retention Time
N	–	Nitrogen
O	–	Oxygen
OHOs	–	Ordinary Heterotrophic Organisms
ORP	–	Oxidation – Reduction Potential
P	–	Phosphorus
PAOs	–	Polyphosphate-Accumulating Organisms
PE	–	Person Equivalents
PHA	–	Poly-β-Hydroxyalkanoate
RAS	–	Return Activated Sludge
rbCOD	–	Readily Biodegradable COD
sCOD	–	Soluble Chemical Oxygen Demand
SRT	–	Sludge Retention Time
SVI	–	Sludge Settling Index
TS	–	Total Solids
TSS	–	Total Suspended Solids
VFA	–	Volatile Fatty Acids
VS	–	Volatile Solids
VSS	–	Volatile Suspended Solids

Preface

This thesis was carried out at the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) in the spring of 2022. A large part of this thesis has been practical laboratory work in the wastewater laboratory of NTNU and is part of work package 1 (WP1) at IVAR in the WIDER UPTAKE project.

First, I would like to thank my supervisor professor Stein W. Østerhus for invaluable insight and knowledge in EBPR and wastewater treatment. You are a walking encyclopedia and a real resource when analyzing results. Secondly, I would give a huge thanks my co – supervisor Dr. Blanca Magdalena Gonzalez Silva for spending so many hours helping me at the lab, encourage me when times were hard and always being there to discuss new solutions when the outcome differ from expectations.

I will also thank Xiaoyang Guo for making sure I had a container full of wastewater for the pilot and making me feel welcome at the lab. Zhitao Huang and Rizza Ardiyanti for your interest in my project and Trine Margrete Hårberg Ness for always making sure I was safe at the lab. Thank you!

Viktoria Røvig
Trondheim, 1th July 2022

Table of content

1 Introduction

1.1 Need for P – removal in wastewater treatment

Phosphorus (P) is essential for human life. It is found in the DNA, cell membranes, and for bone and teeth formation in humans and is vital for food production (Cho 2013). As phosphorous is an element it can neither be destroyed nor created. In agriculture the phosphorus used often come from minded and processed phosphate rock to make phosphoric acid. Ninety percent of the world's mined phosphate rock is used in agriculture and food production and specialist are debating how long these reserves will hold (Taheri 2012). This encourage researches to look for phosphorous other places and wastewater is a place where phosphorous can be found. Urine contains high amount of phosphorus and if not cleaned from the wastewater it may cause problems in the recipient (Cho 2013).

When nutrients such as nitrogen and phosphorus are released with the effluent wastewater into aquatic ecosystems eutrophication can occur (Chislock 2013). Eutrophication is excessive plant and algal growth. Limited sunlight reach thought the water surface when the algae blooms. This could lead to polluted drinking water supplies and degradation of recreational opportunities. When the algae die and decompose the process consumes oxygen in the water body. This creates hypoxic or anoxic 'dead zone' where aquatic organisms lack sufficient oxygen to survive. In Norway it is reported that kelp forests and mussels are gone, seabirds are struggling, and fjords are almost empty of fish (Hansson 2020). This increases the focus on the necessity of wastewater treatment.

1.2 Background

IVAR Sentralrenseanlegg Nord-Jæren (SNJ) is a wastewater treatment plant that treats the wastewater form the Nord-Jæren region in Norway. The treatment plant is designed with Enhanced Biological Phosphorous Removal (EBPR). The treatment plant is not required to remove nutrients but want to be able to recover phosphorus as fertilizer. However, the treatment plant has experienced some challenges with achieving the desirable phosphorous removal. Lab batch experiments has shown great potential for P – removal. Several studies have shown that the main challenge at IVAR is connected to secondary P – release in the settling tank (Lilleland 2019). In order to investigate the matter, it was decided to build a 1:100 lab – scaled pilot of the secondary treatment process at IVAR to optimize the process. The lab – scaled pilot (also referred to as the pilot) will be operated at NTNU in Trondheim.

1.3 Project Aim

The project aim is divided in to two objectives:

1. Startup of the pilot: make the pilot able to have a steady operation by its own.
2. Try to operate the pilot with the same operational parameters as found at IVAR.

The lab – scaled pilot is scaled down 1:100, which means one centimeter in the pilot is equal one meter in the real treatment plant. Downscaling to such small scale is not commonly done. The thesis will therefore aim to answer the following questions:

- Will a lab – scaled pilot with such small dimension be able to operate as an activated sludge process?
- Is it possible to operate the lab – scaled pilot with the same operational parameters as found in IVAR?

1.4 Hypothesis

The lab – scaled pilot is designed to avoid some of the major challenges that is detected at IVAR. This thesis builds on the project work that can be found in Appendix 20. In Appendix 20 both IVAR SNJ and the lab – scaled pilot is described in further detail. The project also describes the challenges found at IVAR and the improvements made in the lab – scaled pilot to avoid the challenges. Some of the main challenges found at IVAR are back mixing between the reactors and secondary phosphorous release in the settling tank. In the lab – scaled pilot the reactors are built with different height to avoid back mixing between the reactors and with a submerged inlet into the aerobic reactor to avoid back mixing of air to the anaerobic zone. The design is described in further detail in Chapter *3.1 Lab – scaled pilot* or Appendix 20. This alteration is done to have more control in every step of the treatment process. The settling tank at IVAR is rectangular while the lab – scaled pilot is built with a circular sedimentation tank. This is to make it easier for the sludge settle in the sludge pocket and thereby avoid long residence time in the settler which will allow for secondary phosphorous release.

Because of the precautions with the change in the design it is expected that the lab – scaled pilot will be able to have more controlled environments and a have better sludge settling in the settling tank. As the sludge used in this experiment is ordered from IVAR it is expected to have the same properties. IVAR reports to have an SVI between 79 – 100, which indicates a good settling. With the changes done to the settlers design it is expected that the sludge will settle good, leaving a cleaned effluent and avoid secondary PO_4-P release. As the sludge is expected to settle and become thick at the bottom of the settler clogging is likely to occur in the RAS flow pipe. This is expected to be the major challenge in the pilot work.

2 Theory

This thesis is based on work done in the specialization project "Lab – Scaled Pilot for Optimization of EBPR". The project can be found in Appendix 20. Some of the theory may be described in greater detail in the appendix.

2.1 Norwegian wastewater characteristics

Typical Norwegian wastewater is highly diluted, cold and low in nutrients (Ødegaard 2014). The characteristics depend on local industry, composition of buildings, season, geographical location and local climate. Coastal areas do often have more diluted wastewater due to combined sewage system and heavier rainfall events. Typical values for Norwegian wastewater can be found in Table 1. For Stavanger the wastewater characteristics are given by domestic wastewater, industrial wastewater, infiltration/inflow containing seawater and stormwater (Danielsen 2018).

Table 1: Norwegian wastewater: Concentrations in [g/m3] for different situations (Ødegaard, 2014).

	Dry weather		Wet weather	
Parameters	**Good condition[1)]**	**Bad condition[2)]**	**Good condition[3)]**	**Bad condition[4)]**
BOD_5	200	120	150	60
COD	400	240	300	120
SS	233	140	175	70
Tot P	6.0	3.6	4.5	1.5
Tot N	40	25	30	12

1) 100 L/pe*d infiltration
2) 300 L/pe*d infiltration
3) 100 L/pe*d infiltration + stormwater = 100 L/pe*d
4) 300 L/pe*d infiltration + stormwater = 700 L/pe*d

2.2 Phosphorus

Phosphorus (P) is a nutrient typically found as organically bound phosphorus or inorganic phosphorus in Norwegian wastewater. The inorganic phosphorus is found as orthophosphate ($[PO_4]^{3-}$) or as polyphosphate ($[P_2O_7]^{4-}$ and $[P_3O_{10}]^{5-}$) and usually make up 80 – 90% of the total P – content. Phosphorus can be removed thought chemical or biological removal.

2.2.1 Chemical P – removal

Chemical removal of phosphorus includes coagulation, flocculation and separation. A coagulant makes particles bound together when added to a flocculation tank. This creates larger flocs that easily can be separated from the effluent by sedimentation, flotation or filtration. Aluminum or iron salts are frequently used coagulants (Ødegaard 2014, 441).

2.2.2 Activated sludge

Activated sludge is a biological wastewater treatment where suspended microorganisms float freely in the reactor and are able to remove substrates from the wastewater. Organic matter found in the wastewater is used as a carbon source for energy and cell growth (Ødegaard 2014, 460). To maintain a suitable concentration of microorganisms in the activated sludge system a Return Activated Sludge (RAS) flow is needed. The RAS makes it possible to maintain a high sludge concentration, low sludge load and a high sludge age (Ødegaard 2014, 468). The RAS is often given in percentage and can be expressed as: $r = Q_{RAS}/Q_{Inf}$ and is usually between 20 – 200 % of the influent flow.

The microorganism flocs together and can reach a size between 50 – 200 mm which makes them easy to remove through sedimentation. Sludge Volume Index (SVI) can be used as an indicator to evaluate the settling properties of the sludge. SVI = 100 – 200 mL/g is typically found in activated sludge plants (Rumbaugh 2019). A low SVI will indicate a good settling.

2.3 Enhanced Biological Phosphorus Removal

EBPR is defined as "*Wastewater treatment biomass removes phosphorous beyond its anabolic requirements by accumulating intracellular polyphosphates (polyP) reserves*" (Svendby 2019). The process utilizes Polyphosphate–Accumulating Organisms (PAOs) to remove phosphorus through cellular growth. In order to achieve this the PAOs are altered between anaerobic and aerobic conditions. Some of the benefits of EBPR are lower operating costs, small reagent–consumption and low sludge production levels compared to chemical precipitation. It is therefore considered a more environmentally sustainable treatment methods (Deng, et al. 2016).

2.3.1 Anaerobic zone

In the anaerobic reactor the PAOs store Volatile Fatty Acids (VFA) to produce intracellular Poly-β-Hydroxyalkanoate (PHA) by linking them together in long chain carbon molecules (Henze, et al. 2008, 159). The VFA found in the reactor originate from the influent wastewater or from anaerobic fermentation of RAS. A hydrolysis of intracellular polyphosphate (polyP) and glycogen catabolism takes place in the PAO (Coats, et al. 2018). The forming of PHA require energy. These anaerobic metabolisms make the PAOs release soluble orthophosphate resulting in an increase in P – concentration in the bulk solution. As orthophosphate level in the anaerobic reactor increases the available VFA level decreases (Barnard and Scruggs 2003). The principle is illustrated in Figure 1.

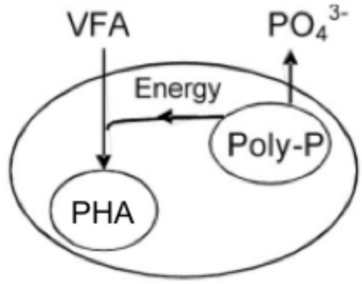

Figure 1: A sketch of the principle of the process in PAOs in anaerobic conditions.

2.3.2 Aerobic zone

In the aerobic zone the PAOs are exposed to oxygen. The oxygen work as an electron acceptor making it possible for the PAO to oxidize PHA to utilize as a carbon energy source and start cell growth. The stored PHA in the cells can also be used as an energy source and starts P – uptake from the bulk solution. The PAOs synthesize poly–P in the new cells making it possible for the PAOs to take up more P than what was released in the anaerobic phase. The biomass containing phosphorus is removed though sedimentation (Henze, et al. 2008, 160). A sketch of the reactions taking place in the aerobic reactor is shown in Figure 2.

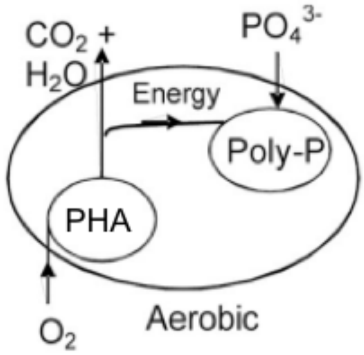

Figure 2: A sketch of the process that find place in the PAOs at aerobic conditions.

2.3.3 Organisms found in EBPR

2.3.3.1 PAOs

The Phosphorus Accumulating Organisms (PAOs) is the most relevant organism for in EBPR. PAOs are used to remove phosphorus from the wastewater by exposure to alternating anaerobic and aerobic environments. The organism is obligate aerobes, which means they need oxygen to grow. A PAO can store approximately 0.38 g P/g VSS (Henze, et al. 2008, 156). There are several different types of

PAOs with different abilities. *Tetrasphaera* and *Accumulibacter* are groups of PAOs that are often fund in EBPR. Candidatus Accumulibacter is the most research form of PAOs and the EBPR process has therefore been adjusted to grow these bacteria. New research shows that more prolonged and deeper anaerobic conditions, may favor growth of other PAOs that behave different than the Accumulibacter (Barnard, Dunlap and Steichen 2017).

Another type of PAO that has been considered for the EBPR process is Tetrasphaera. This is a broad class of bacteria that has still to be well characterized (Barnard, Dunlap and Steichen 2017). The advantage of this bacteria is that they can ferment complex organic molecules such as carbohydrates and amino acids (including glucose, glutamate, aspartate) and produce stored carbon in the process. Unlike the Accumulibacter the Tetrasphaera are able to take up poly – P not only when consuming VFA. They have the ability to takes up VFA as well, but it is not their preferable source of carbon. Under specific anaerobic condition the Tetrasphaera shows the ability to produce VFA which can be utilized by other PAOs. They also show the ability to take up phosphorus in anoxic conditions. An EBPR process that can favor growth of Tetrasphaera will give significant impact on the EBPR process since more of the available carbon could be used for phosphate removal (Barnard, Dunlap and Steichen 2017).

2.3.3.2 GAOs

An undesired organism that also is found in EBPR is Glycogen Accumulating Organisms (GAOs). This organism will compete with PAOs by taking up VFA in the anaerobic reactor but will not perform phosphorus uptake. Glycogen is their primary source of energy. If the process is dominated by GAOs, the P–removal will be poor (Barnard and Scruggs 2003).

Factors that affect the PAO/ GAO competition (Ødegaard 2014):

- Type of C–source
- Influent P/COD–ratio
- pH and temperature
- SRT

It has been observed that the presence of Tetrasphaera in an EBPR process can contribute to a low GAO count in the process (Barnard, Dunlap and Steichen 2017).

2.3.3.3 OHOs

EBPR also include "Ordinary" Heterotroph Organisms (OHOs). OHOs have the ability to remove 10 – 20 % of the phosphorus in the reactor if they are the main organism (Ødegaard 2014). The bacteria are heterotrophic meaning they need oxygen as an electron acceptor. Because of this they do not consume VFAs in the anaerobic reactor and will therefore not compete with the PAOs in this reactor, as long as the condition is completely anaerobic.

2.3.4 Side–stream configuration

Side – stream configuration is a way to operate an EBPR where the RAS flow is not directly put into the same reactor as the influent, but rather into a separate reactor for fermentation. The influent wastewater is connected to the second anaerobic reactor in the treatment train. This allows the microorganisms to ferment without the influence of the influent wastewater and give the right condition for slow hydrolysis of particulate biodegradable organic material to soluble organic compounds such as VFAs (Wang, et al. 2019). As the fermentation happens in a different tank it allows for different retention time for the RAS and the influent water. This can be beneficial on diluted wastewater with low fraction of readily biodegradable organic matter as typically found in Norway (Danielsen 2018).

Access to easy biodegradable carbon is considered a limiting factor in EBPR, and side – stream configuration is a possible solution (Coats, et al., 2018). Studies have shown that this configuration can improve the P–removal performance with up to three times higher P–uptake in the aerobic reactor. It is also shown that the system has a faster recovery after a flush–out storm event. The configuration gives relatively higher PAO activity, as well as glycolysis activity (Wang, et al. 2019).

Denitrification has also been observed in side – stream configuration. Denitrification is described in Chapter *2.5 Nitrogen removal*. OHOs can use nitrate as an electron acceptor and be able to consume the organic material present in the anaerobic reactor (Henze, et al. 2008). This will increase the competition between OHOs and PAOs. Nitrate may also have a negative impact on PAOs metabolism and thereby cause problems with storing polyphosphate (Ødegaard 2014, 484).

2.3.5 Settling tank

A settling tank separate the particles, suspended solids and biological material from the treated wastewater by gravity. Stagnant conditions allow the heavier particles to sink towards the bottom and the clean water to be decanted and discharged into the recipient. The sedimentation basin is an important step in an activated sludge process. The basing helps to produce a clear effluent as well as sufficient thickening of the sludge. In a biological treatment process the thickening is important to be able to deliver sufficient concentration of the RAS (Ødegaard 2014, 436).

2.3.6 Sludge bulking

Sludge bulking is a much – researched subject but is still often experienced in activated sludge systems. As a lot of biological treatment process use sedimentation as a mean for separation the process depends on compact flocs. Bulking sludge is a term often used to describe sludge with excessive growth of filamentous bacteria. Filamentous bulking results in a loose floc structure of the activated sludge, an inability to form stable and dense flocs, a decrease in the sludge sedimentation rate, and lowered sludge compressibility (Li, et al. 2020). They can be identified by long strands with a greater volume and surface than conventional flocs. This porous structure makes it difficult for the floc to settle. Sludge bulking is therefore associated with high SVI. This is mainly caused by the instability and complexity of the environment during the daily operation (Yang, et al. 2013). Activated sludge is a complex ecosystem where 95% of the total microbial population consist of bacteria. If kept under correct environmental conditions the bacteria are able to efficiently remove the organic material and nutrients from wastewater. A volume fraction of 1–20% filamentous bacteria is enough to cause settling problems (Martins , et al. 2004).

2.4 Factors affecting EBPR

2.4.1 Temperature

The temperature will affect the growth rate of microorganisms. Low temperatures usually result in lower grow rate, while too high temperatures may cause the microorganisms to die (Ødegaard 2014). Norwegian conditions have shown to be ideal for EBPR as research done on a range from 5 – 25°C shows better performers on low temperature (Helmer and Kunst 1998). Different temperatures can also favor different types of PAOs. Tetrasphaera seems to be more dominant at lower temperatures, while Accumulibacter can be found in tropical temperatures (Barnard, Dunlap and Steichen 2017). High temperatures (>30°C) has shown to favor the growth of GAOs (Barnard and Scruggs 2003).

2.4.2 pH

pH is one of the factors that affect the competition between GAOs and PAOs in an EBPR process. P–removal increase with higher pH (> 7.25) while low pH will favor GAOs (Barnard and Scruggs 2003). Norwegian wastewater usually has a low alkalinity and pH 7 – 8 and should therefore be ideal (Ødegaard 2014).

2.4.3 COD/P ratio

The COD/P ratio will also affect the competition between GAOs and PAOs. GAOs will be more prominent when the COD fraction in the wastewater is low (such has in periods with heavy rain or snow melting). This is caused by their ability to store accumulated carbohydrates (Barnard and Scruggs 2003). A larger fraction of COD in the influent will help the PAOs to be able to remove larger percentage of phosphorus. The ratio should be lower than 50 mg COD/mg P to favor PAO growth. The recommended interval should be between 15:1 – 25:1 (Wang, et al. 2019).

It is not only the amount of COD, but also the carbon source, which is of interest. Phosphorus removal is better achieved with carbon sources like amino acids, peptone, or yeast extract were added, while GAOs favor polysaccharides, such as glucose (Barnard and Scruggs 2003).

2.4.4 Oxidation – reduction potential (ORP)

Under extended anaerobic conditions, like in side – stream configuration, the Oxidation–Reduction Potential (ORP) may affect the PAO – GAO competition (Varga, et al. 2020). Low ORP can increase the P – removal potential by inhibited the glycogen storage which reduce or eliminates GAOs while PAOs still have the ability to ferment readily biodegradable substrate. This leaves a biomass dominated by PAOs. If combined with low SRT ideal conditions for Tetrasphaera growth occurs. GAOs and PAOs can coexist at ORP ~ –100mV, but at ORP lower than –150 to –200 mV GAOs are disappearing and more stable P–removal occurs (Varga, et al. 2020).

2.4.5 Dissolved Oxygen (DO)

PAOs are obligate aerobes and need aerobic environment to use energy in order to grow and reproduce. In an EBPR process the aerobic reactor gives PAOs a competitive advantage. For this process a DO concentration of 2.5 to 3.0 mg/L has shown good result (Comeau, et al. 1986). Larger concentration increases the risk of oxygen in the RAS flow and the anaerobic reactors which gives a negative impact on the process (Lilleland 2019).

2.4.6 HRT/SRT

Recommended anaerobic Hydraulic Retention Time (HRT) for full scaled plans is typically between 0.25 – 1.0 hour to induce the target metabolisms (Coats, et al., 2011). With longer HRT the risk of VFA depletion increases, which can lead to secondary P – release. This is caused by imbalance of phosphorus released to VFAs stored as PHA, causing insufficient energy available for aerobic phosphorus uptake (Coats, et al., 2011). HRT between 1 – 3 hours has shown enriched PAOs, especially for *Candidatus Accumulibacter phosphatis*.

For activated sludge systems the SRT is linked to the growth rate of microorganisms ($SRT_{min} = 1/\mu_{max}$). SRT for EBPR is depending on several factors like the kinetic rates and processes conditions, time needed in anaerobic phase to convert rbCOD to PHA and the time PHAs need to consume in the aerobic phase. Biomass substrate loading rate, temperature, operation system and cell maximum PHA content does also contribute (Henze, et al. 2008, 201).

The effect of SRT on EBPR performances and stability is still not fully understood and requires further investigation (Onnis-Hayden, et al. 2019). Several studies have been done on the matter. It has been shown that P – content in biomass increases as SRT increases. However, this led to no changes in P removal efficiency. Even though the sludge discharging rate decreased and the amount of PAOs in the system where high with a high phosphorus content inside the PAOs. It has been reported worse settleability of the sludge when the SRT was increased from 8 to 16 days in laboratory – scale systems. It is also observed that the EBPR biomass activity decreased as the SRT was extended, suggesting that shorter SRT is beneficial for PAO and longer SRT favors GAOs. Applying an SRT from 3 to 10 days can result in enriched PAO culture (Onnis-Hayden, et al. 2019).

2.5 Nitrogen removal

As IVAR is not focused around removal of nitrogen (N) and it is therefore not described in Appendix 20. The nitrogen is removed though two steps (Ødegaard 2014, 463):

1) Nitrification that oxidize ammonium to nitrite/nitrate.
2) Denitrification that reduce nitrite/nitrate to nitrogen gas.

2.5.1 Nitrification

In Norwegian wastewater nitrogen is typically found in ammonium and is low on nitrate and nitrite. Therefore, nitrification has to be done before denitrification. The process consists of two reactions. In the first reaction the ammonium is transferred into nitrite using a bacterium named Nitrosomonas. In the second stage nitrite is oxidized into nitrate by Nitrobacter (Ødegaard 2014, 462). The reactions are shown below:

$$NH_4^+ + \frac{3}{2}O_2 = NO_2^- + 2H^+ + H_2O$$

$$NO_2^- + \frac{1}{2}O_2 = NO_3^-$$

$$NH_4 + 2\ O_2 \rightarrow NO_3^- + 2\ H^+ + H_2O$$

The process consume oxygen. If it is not done in the treatment plant the oxygen consumption will happened in the recipient. The process does also consume alkalinity. It will therefore be of interest to do it in the treatment plant before the wastewater is released into a recipient with low alkalinity and oxygen content. Ammonium can also be toxic to aquatic life and should therefore not be released into the recipient if pH is above 8 (Ødegaard 2014).

The reaction is done in aerobic conditions. The bacteria found in nitrification are autotrophic, meaning that they will consume CO_2 as their carbon source. In order to do so the amount of organic material in the reactor has to be low. The nitrifying bacteria are also characterized by a low growth rate that require the process to have a high sludge age (Ødegaard 2014, 463). The SRT correlates to the temperature in the treatment plant. The SRT can be lower for higher temperatures according to Figure 3.

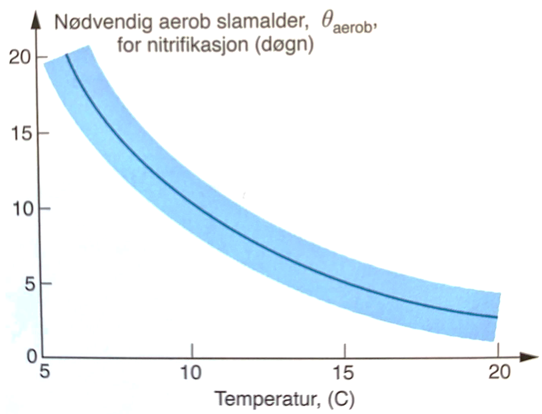

Figure 3: Correlation between temperature and aerobic sludge age to achieve nitrification in an activated sludge plant given an oxygen concentration of 2 mg/L (Ødegaard 2014, 275).

2.5.2 Denitrification

Denitrification is a process that can be found all around in nature where nitrate is naturally found, given no oxygen. In wastewater treatment denitrification is creating nitrogen gas thorough biological reduction of nitrate (Ødegaard 2014, 463). The nitrogen gas is removed from the wastewater when it evades to the air.

Denitrification consist of the following two reactions:

$$3\,NO_3^- + CH_3OH = 3\,NO_2^- + CO_2 + 2H_2O$$
$$2\,NO_2 + CH_3OH = N_2 + CO_2 + H_2O + 2\,OH^-$$
$$\overline{6NO_3^- + 5CH_3OH \rightarrow 3\,N_2 + 5CO2 + 7\,H_2O + 6\,OH^-}$$

The process is anaerobic. However, it is said to be anoxic since it is a modification of the aerobic biochemical decomposition only using nitrite/nitrate as the electron acceptor (oxidizing agent) instead of oxygen (Ødegaard 2014, 464). Most of the denitrifying bacteria are able to live in both anaerobic and aerobic environment. Denitrification can take place with oxygen present. In order to do so all the oxygen supplied must be metabolized by heterotrophic bacteria which do not simultaneously denitrify (Ødegaard 2014, 476).

In order to denitrify an easy biodegradable carbon source is needed. This could be found internal (in the wastewater itself) or external (by adding methanol, ethanol or glycol). The supply of organic matter is often the limiting factor of the denitrification along with the nitrate content in the wastewater.

2.5.3 Pre– and Post–denitrification

Denitrification can be introduced in two ways: pre– or post–denitrification (Ødegaard 2014, 475). In pre – denitrification the denitrification reactor is placed before the nitrification reactor. The nitrate is brought to the denitrification reactor thought a recirculation flow. In post – denitrification the denitrification reactor is placed after the nitrifying reactor. In this configuration an external carbon source is needed, since the wastewater out of the nitrifier do not contain readily biodegradable organic material.

The disadvantage with pre – denitrification is its dependence on the content in the return flow, which leads to a lower removal efficiency with this configuration than in post – denitrification. The pre – denitrification will always contain an amount of ammonium from the influent wastewater, that cannot be denitrified before it has been nitrified. The return flow will also contain oxygen and the access to easy biodegradable carbon is limited by what is found in the influent. To accommodate these factors the pre – denitrification reactor has to have larger dimensions than post – denitrification. The main disadvantage with post – denitrification is its need for an external carbon source. One does also have to adjust the alkalinity of the wastewater. It is therefore possible to combine pre– and post–denitrification to utilize the benefits with both configurations.

2.6 IVAR SNJ

IVAR Sentralrenseanlegg Nord – Jæren is the wastewater treatment plant for Stavanger, Sola, Sandnes, and Gjesdal. It has a capacity of 400 000 Person Equivalents (PE) (IVAR 2018). Their goal is to turn the wastewater into a useful resource by producing biogas and fertilizer. In order to reach the secondary treatment goal, the plant use activated sludge. They have also included EBPR for removal of phosphorus and be able to recycle it as a resource for sale. The plant is not designed for nitrogen removal. A detailed description of IVAR SNJ is given in Appendix 20.

2.6.1 Design

The treatment plant is divided into three treatment lines (L1, L2 and L3). Figure 6 shows a flow sheet for one of the treatment lines. The raw wastewater has to first go through a sieve before it reaches a sand and grease trap. It is then filter through a drum filter before it reaches the biological treatment. The biological treatment is divided in to three anaerobic reactors (An1, An2 and An3) and one aerobic reactor. IVAR utilize side–stream configuration, where the influent water from the primary treatment enters An2 and the RAS enter An1 where it gets fermented. HRT for An2 and An3 is equal, as well as the HRT for the aerobic reactor, since they all receive the same flow (Lilleland 2019). The plant has a possibility to operate with different RAS flows, and the HRT in An1 correspond to the RAS pumping rate. A rectangular settling tank is found at the end of the treatment line. The sludge is collected in the sludge pocket and returned as RAS to An1 or sent to sludge treatment as surplus sludge (Danielsen 2018, 23). The settling tank can be driven with intermittent settling so that the sludge can thickens before it is sent as RAS.

Some of the challenges that has been observed at IVAR is problems with back mixing, such that oxygen enters An3. It is also discovered that the inlet of the sedimentation tank has unfavorable inflow conditions, causing the sludge to settle far away from the sludge pocket. Combined with limited capacity of the sludge scrapers the sludge get caught in the settler for long enough time to cause secondary P – release.

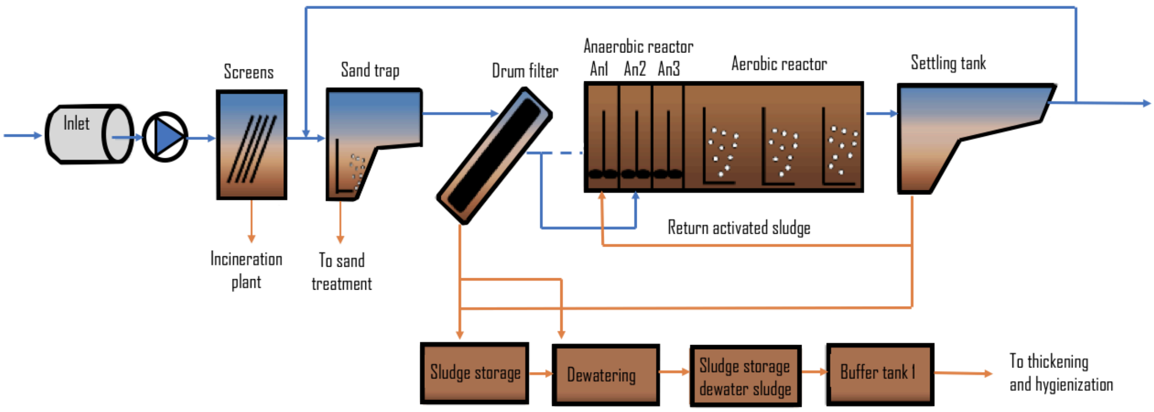

Figure 6: Flow sheet of one process line found at IVAR SNJ.

2.6.2 Operation parameters at IVAR

Some of the average operation values provided by IVAR is listed in Table 2. The parameters will vary depending on season and weather. To provide a deeper understanding of the variations that occurs in IVAR, Table 3 list minimum and maximum values found in a dataset covering three years of operation. In addition, IVAR reports to use a RAS flow equal to 25 % of the influent flow.

Table 2: Operational parameters for normal operation at IVAR SNJ

	Raw ww	After primary treatment	Unit
Q	103 00	103 000	m^3/d
PO_4-P	1,97 – 2	2	mg/L
Tot P	4,29	4,0	mg/L
Tot COD	368	225	mg/L
sCOD	82	80	mg/L
TSS	234	124	mg/L
Temp.	12 - 15	12 – 15	°C
DO	1 – 3	2 – 4	mg/L
Seawater	4,5	4,5	%
Conductivity	3,05	3,05	mS/cm
pH	≈ 7,5	≈ 7,5	

Table 3: Minimum and maximum values found in a dataset of IVARs operation between 04.01.18 to 08.04.21.

	Max	Min	Unit
Tot BOD	530	68	mg/L
sBOD	79	10	mg/L
sCOD	136	31	mg/L
totCOD	652	114	mg/L
SS	852	71	mg/L
Tot P	6	1	mg/L
PO_4-P	3	1	mg/L

The Q given in Table 2 is divided in to the three treatment lines in the plant. The flow found in each line would be:

$$Q_{\text{line}} = \frac{103\ 000\ m^3/L}{3} = 34\ 333\ \text{m}^3/\text{d}$$

IVAR operates with an average temperature equal to 8 – 12 °C and the pH is 6.5 – 7.6. They report to have a COD/P ratio equal to 17 – 33 mg/mg (Lilleland 2019).

IVAR reports to have really good settling properties for the sludge. They have an SVI between 79 – 100 with an average ≈ 90 mL/g. The thickened sludge found as WAS can be 12 – 15 000 mg/L SS in the sludge tank (Lilleland 2019).

3 Methods

3.1 Lab – scaled pilot

The lab–scaled pilot (the pilot) is a 1:100 model of IVAR SNJ. One centimeter in the pilot is equal to one meter in the full–scaled plant. A flow sheet of the lab – scaled pilot is shown in Figure 7. The pilot will utilize water from the municipal sewage network in Trondheim with additional added seawater to mimic the conditions at IVAR. The pilot is operated inside the wastewater lab. As the dimension are small the wastewater is expected to hold room temperature. A detailed description of the lab – scaled pilot is given in Appendix 20.

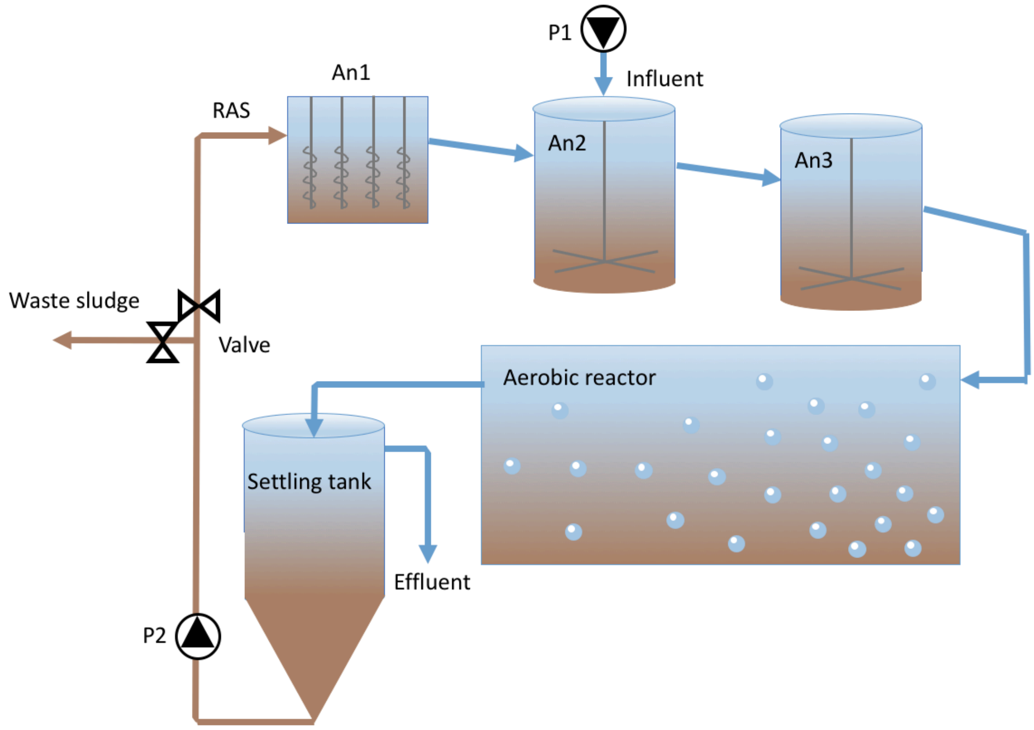

Figure 7: Flow sheet of the treatment train in the lab-scaled pilot.

A picture of the lab – scaled pilot is shown in Figure 8. The pilot includes three anaerobic reactors, on aerobe reactor, a circular settling tank with return activated sludge flow, two pumps, and a valve to control RAS and waste sludge flow. As primary treatment the wastewater is filtered through a Brandos Salsnes filter at the lab and sludge treatment is not included.

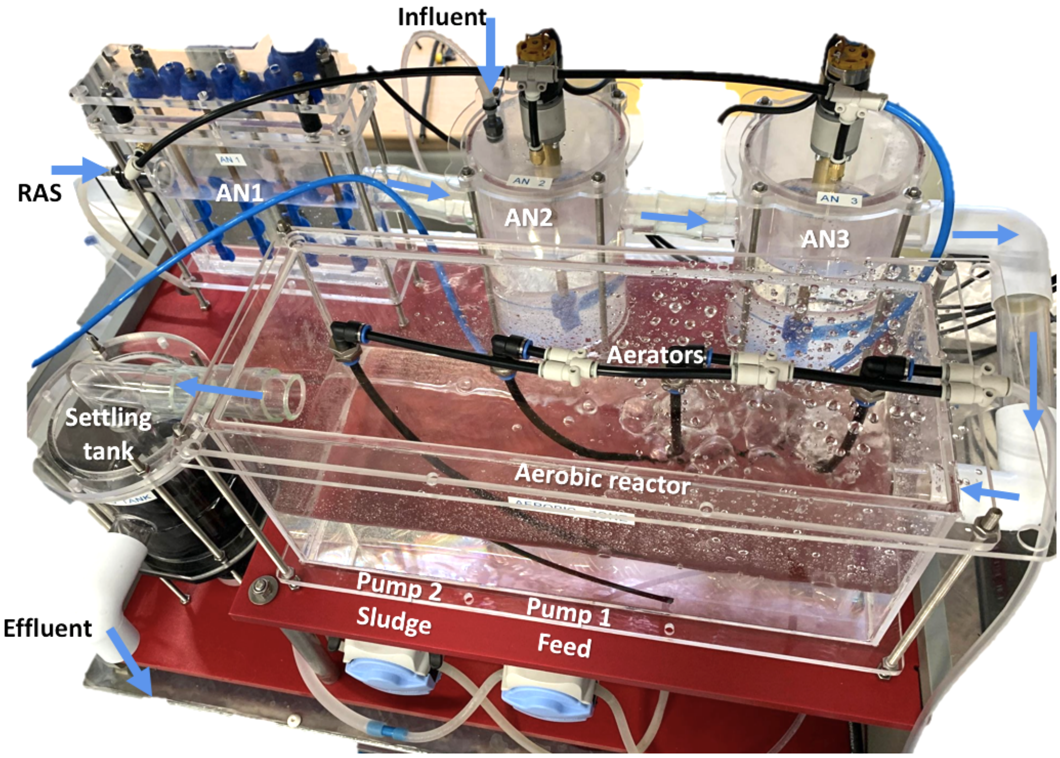

Figure 8: A picture of the lab - scaled pilot. The picture is taken before the pilot has been operated with wastewater. Note that the aeration system seen in the picture is not used during the experiment period.

3.1.1 Design Lab – scaled pilot

As IVAR the lab – scaled pilot has three anaerobic reactors. These are shown in Figure 9. The 3D printed stirrers and the pumps are controlled through a control panel. An2 and An3 are connected to the same motor and would be driven on the same speed while An1 has a separate motor and can therefore have a different speed. The stirring speed in the lab – scaled pilot should be enough for the sludge not to settle, but not so fast that it causes foaming.

The design of the anaerobic reactors in the lab – scaled pilot deviates from the original reactors at IVAR as they have the possibility to add nitrogen gas to the reactor to achieve totally anaerobic conditions. This feature is adjustable and possible to turn on as needed. The reactors are placed on different height levels, which are adjustable, and use gravity to avoid back mixing. Dimensions of the design of An1 and An2 (An3) can be found in Appendix 1.

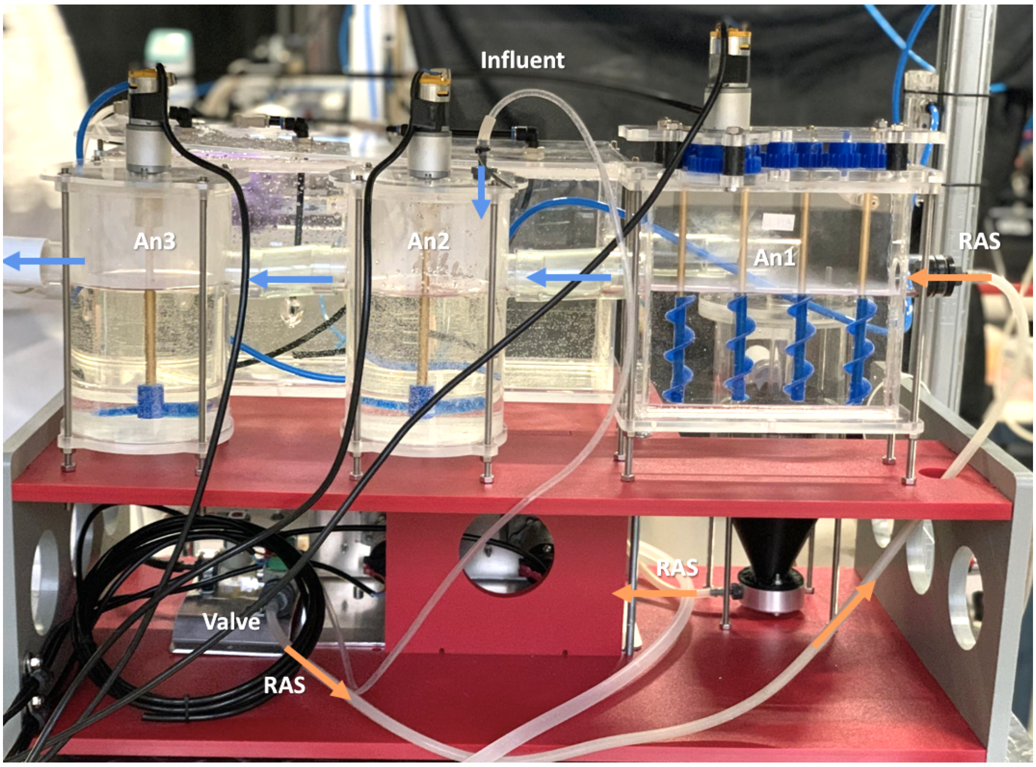

Figure 9: A picture of the anaerobic reactors before inoculation.

The lab – scaled pilots' aerobic reactor is shown in Figure 10. To avoid oxygen going from the aerobic reactor to An3, a submerged inlet was chosen. The aeration system shown in this picture has not been used in the operation of the pilot. The dimensions of the reactors are given in Table 4 and a drawing can be seen in Appendix 2.

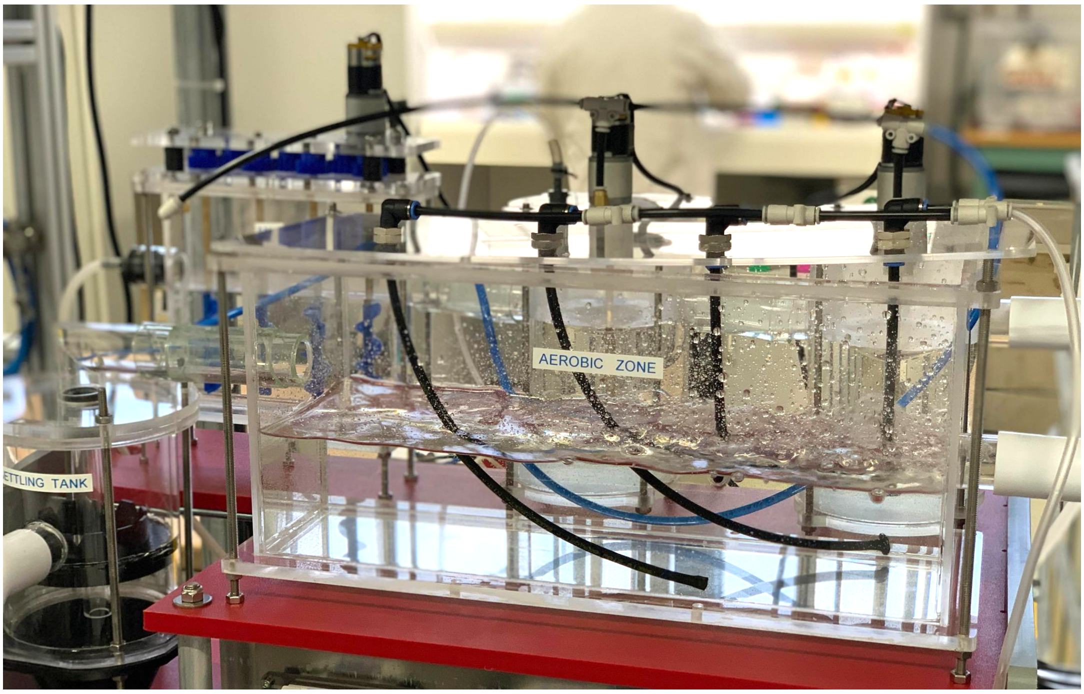

Figure 10: The picture shows the aerobic reactor. The aeration system shown in this picture has not been used during the experiment period.

Table 4: Dimensions of the anaerobic reactors and the aerobic reactor in the lab - scaled pilot.

	Length [cm]	With [cm]	Hight [cm]	Hight inn/out [cm]	Calculated volumes ≈ [cm^3]
An1	18.39	2.9	17.1	9.1	485
Aerobic	40.2	14.4	18.3	9.3	5200
	DIAMETER [cm]				
An2	10.9			10	930
An3	10.9			10	930

The settling tank of the lab – scaled pilot has a different design than the settling tank at IVAR and is shown in Figure 11. A circular sedimentation tank has been introduced to overcome the challenges connected to hydraulic and the long retention time that has been observed in the full–scaled plant. It is also designed so that the sludge will settle in the sludge pocket. As the sludge settle at the bottom of the sedimentation tank it will be pumped as RAS to An1 or wasted and the cleaned water is decanted. The settling tank dimensions are given in Table 5. A drawing of the settling tank design and its dimensions can be found in Appendix 2 and Figure 11 shows a picture of the tank.

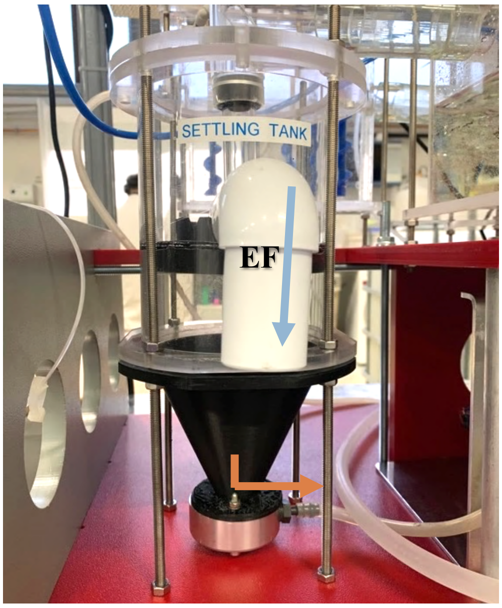

Figure 11: The picture shows the settling tank for the lab - scaled pilot.

Table 5: Dimensions of the settling tank for the lab - scaled pilot.

	Diameter [cm]	Hight cone [cm]	Hight cone to inlet outlet [cm]
Settling tank	11.4	9.87	6.2

The valve described in Appendix 20 was changed before inoculation. This was done because the earlier valve easily became clogged. The new valve is shown in Figure 12. The new configuration also made it easier to determine if the valve was open.

Figure 12: A picture of the RAS and WAS valve for the lab - scaled pilot.

The lab – scaled pilot can be controlled though a control panel, which is shown in Figure 13. Pump 1 (P1) is the feed pump and Pump 2 (P2) is the sludge return (RAS) and waste flow. An1 and An2 – 3 controls the stirring mechanism in those reactors and the valve controls how often sludge is wasted or send as RAS to An1. All of the parameters have one button to control the speed and another to control the on/off frequency. The datasheet for the panel is attached in Appendix 3. A parts list of different components found in the control panel of the lab–scaled pilot is given in Appendix 4. The lab – scaled pilot uses a pump by RC Components. The pump specification can be found in Appendix 5.

Figure 13: Control panel for the lab - scaled pilot.

3.1.2 Flows

3.1.2.1 Influent

The calculated flow per line given in Chapter *2.6.2 Operation parameters* was $34\ 333\ m^3/d$. To fit the 1:100 scale it must be divided by 10^6. This provides an influent flow equal to:

$$Q_{inf.pilot} = \frac{34\ 333\frac{m^3}{d} * 1000\ L/m^3}{10^6} = 34.33\ L/d$$

$$Q_{inf.pilot} = \frac{34{,}33\frac{L}{d} * 1000\frac{ml}{d}}{1440\frac{min}{d}} = 24\ ml/min$$

3.1.2.2 RAS

IVAR reports to use a RAS equal to 25 % of the influent flow. That RAS flow for the pilot is then:

$$Q_{RAS} = 24\frac{ml}{min} * 0.25 = 6\ ml/min$$

3.1.2.3 WAS

IVAR reports to have an aerobic sludge age (SRT) equal to 3.3 days. Appendix 6 shows the calculation of the WAS volume based on this sludge age. This gives a WAS flow equal to:

Q_{WAS} = 446 ml/d

The WAS flow is controlled by the valve. The valve opens ever third hour for a length of 10 minutes.

3.1.3 HRT

The HRT for the reactor is found by using the following formula:

$$HRT = \frac{V}{Q}\ [min] \tag{1}$$

HRT: Hydraulic Retention Time

V: Volume of reactor

Q: Flow

The calculation for the HRT can be found in Appendix 7. The resulting HRT is listed in Table 6.

Table 6: The calculated HRT for each treatment step in the lab – scaled pilot.

Fermentation	Anaerobic	Aerobic
1h 23 min	1 h 16 min	3 h 52 min

3.1.4 Influent wastewater

A container of 1000 L of influent wastewater was prepared each week. The raw wastewater was diluted in accordance with the raw influent wastewater characteristics provided in Appendix 8. Both the $PO_4 - P$ level as well as the sCOD level is higher in Trondheim than in Stavanger. It was therefore decided to dilute the wastewater so that the sCOD level would be similar to the level found in Stavanger. The calculation could be found in Appendix 9. Table 7 provides the mixture of dilution and added seawater found in the container in the period from 10.03.2022 until 10.05.2022. The composition found in the table will be referred to as "the influent wastewater" while "raw influent wastewater" will refer to the filtered wastewater before dilution and adding of seawater.

Table 7: The influent wastewater container content in the period 10.03.2022 until 10.05.2022.

	Filtered wastewater (L)	Seawater (L)	Tap water (L)
Container	710	60	230

3.1.5 Sampling

The sampling for the influent wastewater is taken at the inlet point into the pilot. All effluent samples are taken at the outlet of the decanted water. Aerobic samples are taken in the aerobic chamber and RAS and WAS samples are taken after the outlet point at the bottom of the settling tank. All soluble samples are filtered with a 0.45 µm filter immediately after sampling to prevent further reactions.

3.1.6 P/VS ratio

P/VS is a parameter often used to evaluate the EBPR performance (Henze, et al. 2008, 198). The parameter indicates how much of the biomass that consist of PAOs. When the number increase, the amount of PAOs relative to OHOs increases.

$$\frac{P}{VS} = \frac{c_{TP} - c_{PO_4-P}}{VS_{AE}} \tag{2}$$

c_{PO_4-P} : concentration of PO_4-P in aerobic chamber
c_{TP} : concentration of total P in the aerobic chamber
VS_{AE} : VS in the aerobic chamber

3.1.7 Calculation of PAOs

As the main removal of P comes from PAOs it is of interest to see how much of the biomass that consists of PAOs. This can be found by the following formula:

$$P/VSS_{Ae} = \frac{P_{PAO} * X + P_{OHO} * (1 - X)}{VSS} \tag{3}$$

VSS: The amount of VSS in the aerobic chamber.
X: Amount of PAOs.
P_{PAO}: The amount of P a PAO can uptake. A PAO can store up to 0.38 g P/g VSS (Henze, et al. 2008, 156). For this calculation the PAO capacity is set to 0.3 g P/g VSS.
P_{OHO}: The amount of P taken up by OHOs. This will vary depending on the OHOs found in the solution. For this calculation 0.015 g P/g VSS is used.
P/VS: Calculated as explained in 3.1.6 P/VS ratio.

For the purpose of approximately calculating the amount of PAOs in the pilot it is assumed that VS ≈ VSS. Rearranged for the formula to give the amount of PAOs:

$$X = \frac{\left(VS * \frac{P}{VS}\right) - P_{OHO}}{P_{PAO} - P_{OHO}} \left[\frac{mg}{L}\right] \tag{4}$$

3.1.8 Inoculation

The pilot was inoculated to get the same TS levels as IVAR reports to have. Table 8 shows the desired TS values for each of the reactors together with the pilot reactor volumes.

Table 8: The desired amount of TS in each reactor and the volume of the lab – scaled pilot reactors.

	An1	An2	An3	Aerobic
TS [mg/L]	10 000	2 000	2 000	2 000
V_{pilot} [L]	0.5	0.9	0.9	5.5

The sludge used for inoculation was ordered from IVAR. The characterization of the sludge can be found in Appendix 10. The pilot had been operated with wastewater for 24 h before the inoculation.

It was found that the settled sludge volume at 4 L had a TS ≈ 8500 mg/L. The amount of sludge needed to be added to each reactor is found by:

$$c_1 * V_1 = c_2 * V_2 \qquad (5)$$

By using Equation 5, the necessary inoculation sludge volumes are:

$$V_{An1} = \frac{10\,000 \frac{mg}{L} * 0.5\ L}{8500\ mg/L} = 588.3\ ml$$

$$V_{An2} = V_{An3} = \frac{2000 \frac{mg}{L} * 0.95\ L}{8500\ mg/L} = 223.5\ ml$$

$$V_{Ae} = \frac{2000 \frac{mg}{L} * 5.5\ L}{8500\ mg/L} = 1294\ ml$$

This gives a total sludge volume of V_{tot} ≈ 2330 ml. The remaining sludge was added to the settling tank. Appendix 11 shows the calculated amount of TS that is added to each reactor.

3.2 SVI

The SVI is calculated by the following formula:

$$SVI = \frac{Setteled\ sludge\ Volume\ \left[\frac{ml}{L}\right]}{Mixed\ Liquid\ Suspended\ Solids\ \left[\frac{g}{L}\right]} \tag{6}$$

The sludge volume index is found by filling a graduated cylinder with 1 L of mixed sludge and let it settle for 30 minutes (Ødegaard 2014, 470). The volume of settled sludge is the Settled sludge Volume (SV). The Mixed Liquid Suspended Solids (MLSS) is found by using the method for determination of solids described in Chapter *3.4 Determination of solids*.

3.3 SRT

The sludge retention time (SRT), also referred to as the sludge age, is found by using the same method for determination of solids described in Chapter *3.4 Determination of solids* and finding the WAS flow. The SRT is calculated using the formula:

$$SRT = \frac{V * X}{Q_w * X_r} \tag{7}$$

V: volume of reactor

X: TS in aeration tank

Q_w: Waste sludge flow rate from return line

X_r: TS of sludge in return line

Note that this formula neglects the effect of sludge in the effluent as it assumes that the sludge in the effluent is low.

To maintain a low SRT the excess sludge produced each day must be wasted. This is done through the WAS flow.

3.4 Determination of solids

3.4.1 Total solids

The total solids were determined by using Standard Methods 2540 B (American Public Health Association 2017). Analyses were made by performance duplicates and taking the average value of all valid samples. Samples that deviate more than 5% were discarded. All clean dishes were heated until 550°C before preforming the determination. The formula used for calculation is:

$$TS = \frac{(A - B) * 1000}{V_{sample}} \tag{8}$$

TS: Total solids [mg/L]
A: Weight of dried dish and residual [g]
B: Weight of dish [g]
V_{sample}: Volume of sample [L]

3.4.2 Volatile solids

Volatile solids where determined by using Standard Methods 2540 E (American Public Health Association 2017). Analyses were made by performance duplicates and taking the average value of all valid samples. Samples that deviate more than 5% were discarded. The formula used for calculation is:

$$VS = \frac{(A - B) * 1000}{V_{sample}} \tag{9}$$

TS: Total solids [mg/L]
A: Weight of dried dish and residual before ignition [g]
B: Weight of residue + dish after ignition [g]
V_{sample}: Volume of sample [L]

3.5 The TS from salt

As seawater is added to the influent wastewater a considerable amount of the TS found in the samples will consist of salt. The average salt content in seawater is 35 g/L (National Weather Service u.d.). 60 L of seawater is added to the 1000 L container. The salt concentration found in the influent wastewater will be:

$$c_{salt} = \frac{60\,L * 35\,g/L}{1000\,L} = 2.1\frac{g}{L} = 2100\,mg/L$$

This large amount of salt makes it not possible to rely on TS for matter that concerns biomass. Because of this VS is used instead of TS on several occasions.

3.6 Temperature, pH and conductivity

The pH and conductivity were determined using the Hach HQ440d Laboratory Multi-Meter. pH was measured with a portable pH meter.

3.7 Kinetic batch experiment

All kinetic batch experiments were performed on sludge from the aerobic chamber of the pilot. The experiments are performed in a 1000 ml beaker. Sludge was taken from the aerobic chamber of the pilot while evenly mixed and left to settle until it reached a sludge volume equal to 400 ml. When settled the excess water was removed using a hose and a laboratory rubber suction ball to avoid disturbing the settled sludge. 600 ml of wastewater was then added to the batch. Some of the experiments were performed with raw influent wastewater, while others were using the container influent wastewater. The experiments were performed in beakers with custom made lids, using magnetic stirrers at 150 rpm to ensure evenly mixing. The experiment is conducted in room temperature. A picture of the setup is shown in Figure 14.

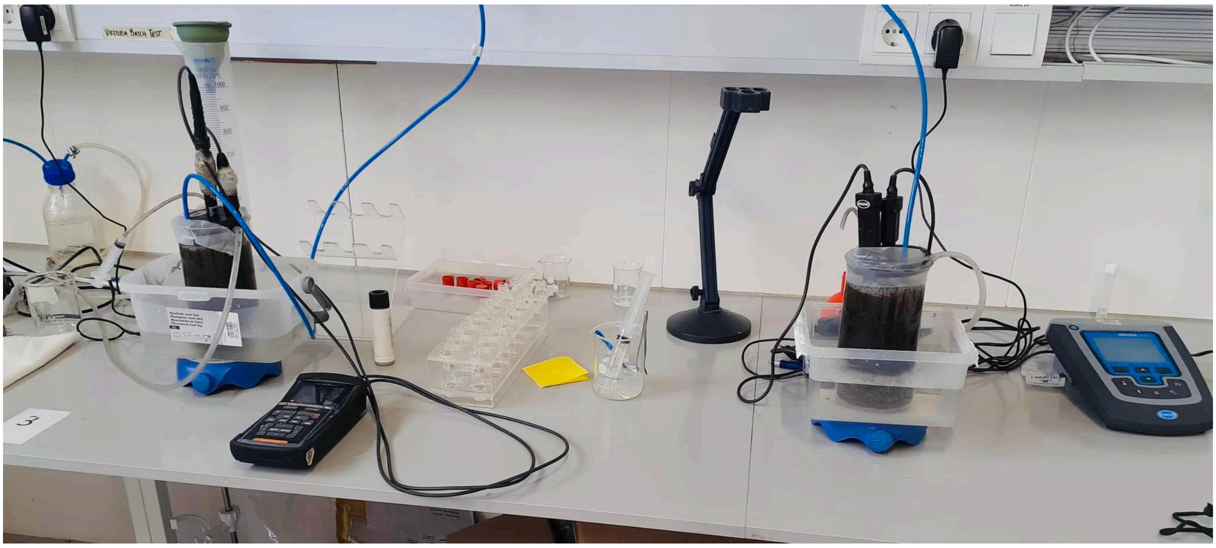

Figure 14: The picture shows the setup of the Batch experiment. Note that the containers of water were not included in the experiment conducted in this thesis.

3.7.1 Anaerobic condition

The anaerobic HRT for the experiment is equal to the HRT for the anaerobic phase of the pilot which is 1h 16min. The lids were sealed with Parafilm to avoid air. Nitrogen gas was added to the batches to ensure anaerobic conditions. Samples were taken every 15 minutes through a hole in the lid and immediately filtrated. For all experiments comparing Batch 1 and Batch 2 the sludge was taken from the aerobic chamber the same day and they use the same influent wastewater in both batches.

3.7.2 Aerobic condition

When the anaerobic HRT is done the lids are opened and the nitrogen gas removed. Air is added to the batch through an aquarium air pump. The HRT is 3h 52min and is equal to the aerobic retention time of the pilot. Samples are taken every hour.

3.7.3 Experiments with acetate

In some of the experiment's acetate is added to see the effect of increased VFA on the P – removal. The calculation of the necessary amount can be found in Appendix 12. The acetate is added at the start of the experiment. The rest of the experiment is performed as usual.

3.7.4 Experiments with fermented sludge

It was of interest to see how the fermentation reactor affected the pilots' ability to remove P. The sludge was taken from the aerobic reactor, settled down to 400 ml and the excess water was removed as described earlier. The sludge was then left in a sealed beaker with nitrogen gas and evenly mixing for 1h 23 min. After the fermentation 600 ml of wastewater was added and the experiment continued as previously explained.

4 Results

4.1 Stage 1: Inoculation

The sludge characteristics for the IVAR sludge can be found in Appendix 10. The lab – scaled pilot was inoculated with the sludge volumes calculated in Chapter *3.1.8 Inoculation*. The lab – scaled pilot operated with an influent flow equal to 24 ml/min. The RAS flow was 25 % of the influent.

4.1.1 Performance

The immediate reaction after inoculation was that the pilot seemed to be working well. It performed with a good distribution of sludge and correct flows when kept under observation. However, when left to operate by its own the RAS flow soon became diluted. The sludge had been distributed at inoculation. After several retention times the sludge would settle in the aerobic chamber, leaving the anaerobic reactors and the settling tank almost clear. This is shown in Figure 15.

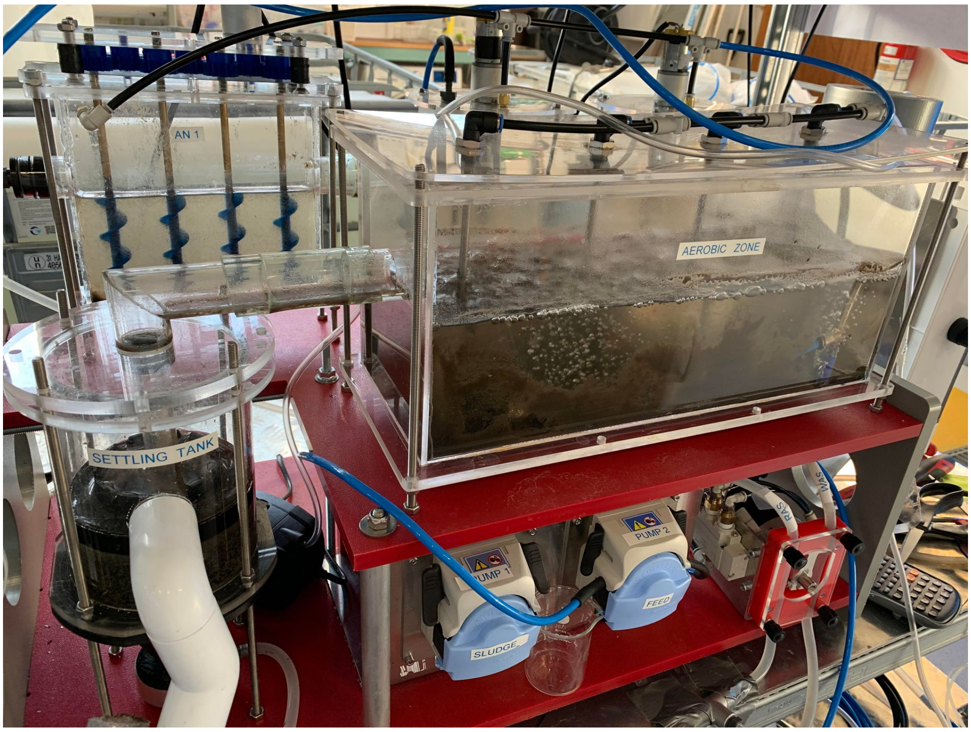

Figure 15: The picture shows how the pilot looked in Stage 1 after left to operate by its own. All chambers are diluted and most of the sludge has settled in the aerobic reactor.

An1 was supposed to have a concentration equal to 10 000 mg/L. Figure 16 shows An1 at inoculation compared to the concentration after serval retention times. The image shows almost none sludge in the reactor.

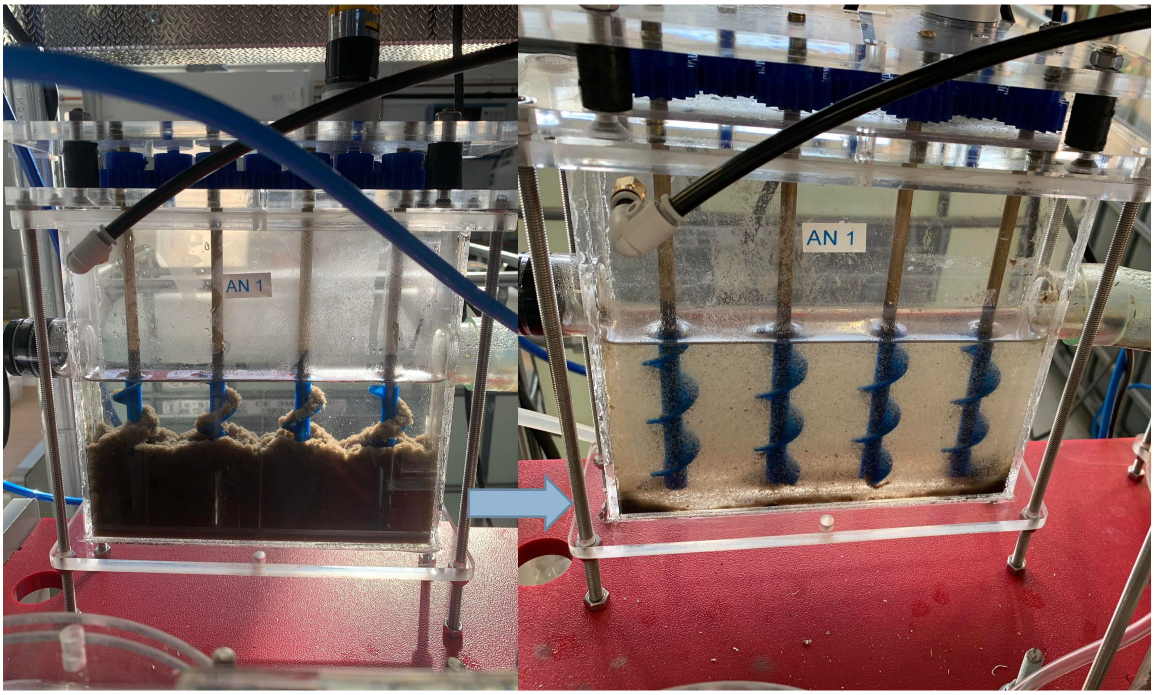

Figure 16: Closeup of An1 after inoculation before the stirrers are turned on compared to close up of An1 after left to operate alone. The sludge in the reactor has become highly diluted.

As the pilot was not able to operate under stable conditions it is important to note that the following calculations that depends on TS or VS are found when the pilot was supervised, and correct operation were ensured. These values will indicate how the pilot performance would have been given that the sludge did not settle in the aerobic chamber. However, they will not be representative for the pilot actual performance due to the dilution.

4.1.2 P – removal

The P – removal is a parameter that is possible to test even when the pilot is at an unstable state. A sample of the influent and effluent of the pilot was taken and the result can be seen in Table 9. As expected, the removal was low.

Table 9: The table shows the P-removal in the pilot in Stage 1.

Influent (mg P/L)	**Effluent** (mg P/L)	**Removed** (mg P/L)	**% P-removed** (%)
4.21	4.18	0.03	0.7

4.1.2.1 P/VS

P/VS is a parameter of interest. As the parameter was tested soon after inoculation one can assume that its value will be close to what can be found at IVAR. Table 10 shows that the P/VS content in the sludge is 1.45 %. Note that this is a parameter depending on VS and will be found under supervision.

Table 10: The table shows P/VS for the pilot in Stage 1.

PO4-P (mg P/L)	**Tot P** (mg P/L)	**VS** (mg/L)	**P/VS** (%)
3.68	27.4	1636	1.5

4.1.2.2 PAOs

By using the values found in Table 10, it is possible to calculate an amount of PAOs in the sludge. Using Equation 4 gives following results:

$$PAO = \frac{(1636\ mg/L * 0.015) - 0.015\ gP/gVS}{0.3\frac{g\ P}{g\ VS} - 0.015\frac{g\ P}{g\ VS}} = \text{83 mg/L}$$

4.1.3 SRT

The SRT is a parameter that is depending on TS or VS and may therefore not be as representative for the situation in the pilot. As the sludge is settling in the aerobic chamber one can expect that the real SRT will be high, as the sludge stayed in the chamber for a long period of time and the WAS flow as well as the RAS flow was very diluted. This can easily be seen from the Equation 7. When X_W (the concentration of RAS) gets more diluted and the number decrease, the SRT will increase.

The SRT is still calculated to gain knowledge of how the pilot could have performed if not for the operational challenges. The TS and VS is therefore found under supervision that ensured correct operation, distribution in all reactors and thicker RAS flow. The SRT calculated is shown in Table 11.

Table 11: The table shows the different SRT for both the whole pilot and for the aerobic reactor calculated with TS and VS for Stage 1.

Aerobic		**RAS**		**WAS**	**Pilot SRT**		**Aerobic SRT**	
TS_{AE} [mg/L]	VS_{AE} [mg/L]	TS_{RAS} [mg/L]	VS_{RAS} [mg/L]	V_{WAS} [ml]	$SRT_{p.TS}$ [days]	$SRT_{p.VS}$ [days]	$SRT_{AE.TS}$ [days]	$SRT_{AE.VS}$ [days]
3688	1636	6132	3066	580	7.7	6.8	5.7	5.1

In Chapter *3.5 The TS from salt* the salt concentration in the influent wastewater is calculated to be 2100 mg/L. The difference between TS and VS found in Table 11 is 2 638 mg/L, which means most of TS removed consisted of salt. It is therefore most reliable to use VS to evaluate the SRT. The aerobic SRT found under supervision was found to be 5 days, which is close to the intended value.

4.1.4 Discussion

The diluted reactors are due to operational difficulties associated with low turbulence in the aerobic reactor. By the tests performed during supervision, the pilot seemed to be able to operate with close to the same conditions as IVAR given that the operational problems are solved.

The P/VS content found in the sludge was surprisingly low as the typical value found in activated sludge is 0.02 mg P/mg VSS (Henze, et al. 2008). For EBPR it is possible to reach 0.06 – 0.15 mg P/mg VSS. With 0.15 mg P/mg VSS up to 40% of the active organisms can be PAOs and have the ability to remove 10 – 12 mg P/L pr 500 mg influent COD (Henze, et al. 2008). The P/VS ratio is affected by the low VS in the sludge. This may be caused by several factors, like the low RAS flow. The sludge that arrived from IVAR did also have a low VS content. The inoculation was calculated based on TS, as this is the operational parameter IVAR has specified. However, since 2100 mg/L of the TS amount is salt it will not contribute to the biomass.

It is observed that less sludge is settled in the areas were the concentration of air bubbles are high. A hypothesis for why the sludge settles in the aerobic chamber is lack of turbulence due to clogging. It is also noticed that the aeration system is connected with metal joints in all corners. No air is distributed at the joints, which leads to no turbulence and causes the sludge to settle. The metallic joint is shown in Figure 17. One can also observed that the joint is elevated from the bottom of the reactor, leaving a space for sludge pockets to form.

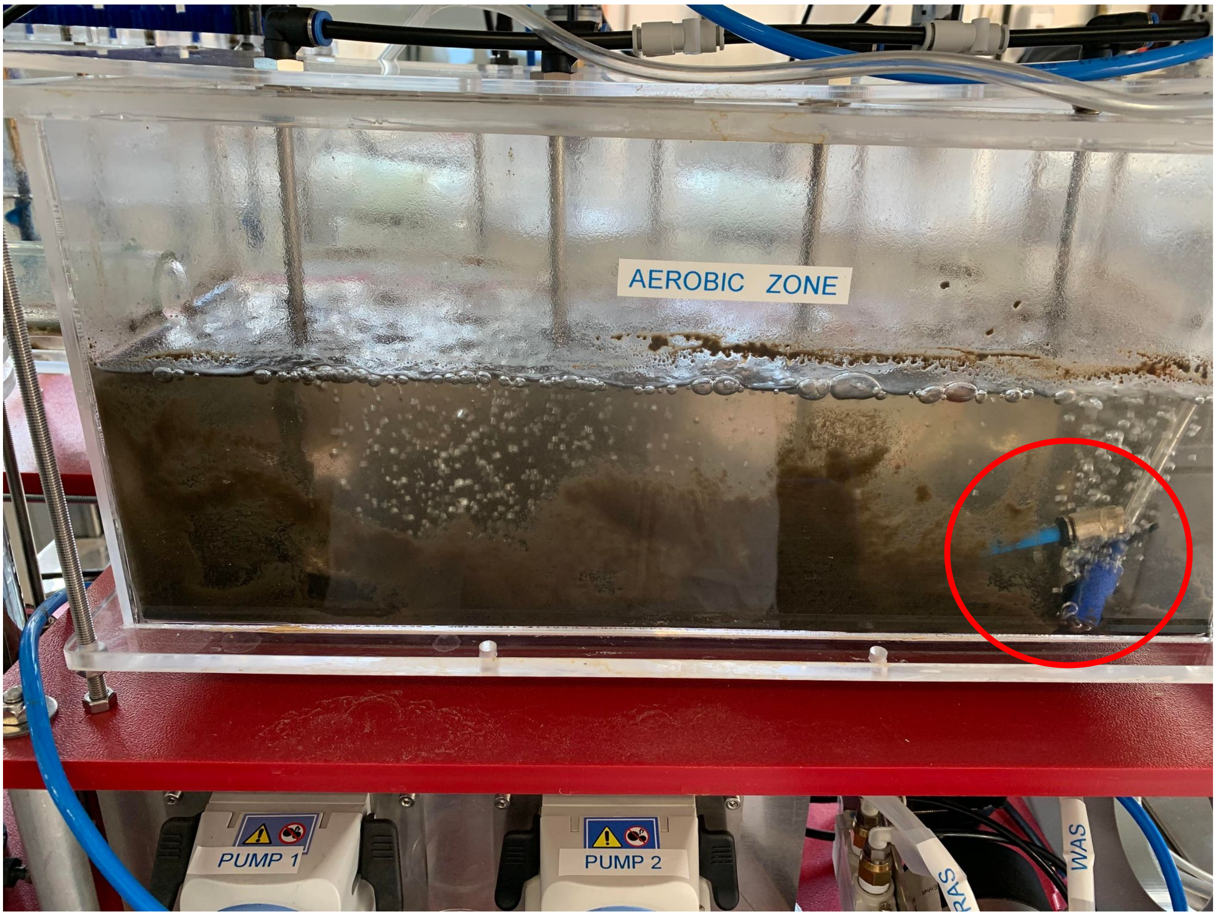

Figure 17: Closeup of the anaerobic reactor shows the metallic joint on the aeration system. Note that in the picture an external aerator is added at that point in order to counteract the lack of air from the joint. Where external aeration is not added it is not possible to see the metallic joints due to the settled sludge.

Another theory that may contribute to the dilution of the anaerobic chambers is forming of water channels in the settler. If this is the case the RAS flow will still be diluted even if the sludge settles adequately in the settler. It is not possible to see how the sludge settles since the bottom of the sedimentation tank is not transparent.

4.2 Stage 2: Intermittent RAS pumping and adjustable aeration pressure

To solve the problems found in Stage 1 some changes were implemented. The RAS flow at 6 ml/min was originally achieved through a small on/off frequency on the pump provided with the pilot. In order to try to increase the concentration of sludge in An1 the pump was changed to a peristatic pump. An intermittent pumping rate of 10 min on and 10 min off was introduced in order for the sludge to settle and become compact. The pump speed was increased to twice the flow to compensate for the time off and still provide an average RAS flow of 25 % of the inflow. This was done in order to reduce eventual water channel forming in the settler.

An aeration system with the ability to regulate both air pressure and flow was introduced. By being able to increase the pressure it should be possible to avoid system clogging and therefore ensure turbulence in the aeration tank. Having the ability to adjust the air flow also makes it possible to modify the DO in the reactor. The design of the aeration system was changed in order to get the same elevation at all points, avoid metal joints and ensure good distribution throughout the reactor.

4.2.1 Performance

Figure 18 shows the pilot after implementing the changes and left to operate by its own. The sludge concentration in the anaerobic reactors are higher than what was seen in Stage 1, but the concentration is still highly diluted. Problems with settling of sludge in the aerobic reactor was still occurring. In Stage 2 several different air flows and pressure were tested in order to cause more turbulence and avoid the suspected clogging. None of the tests led to increased sludge distribution. Long strands of flocs were observed in the aerobic reactor that may resemble filamentous sludge. Due to the extended residence time in the aerobic reactor it is not unexpected if filamentous bulking occurs.

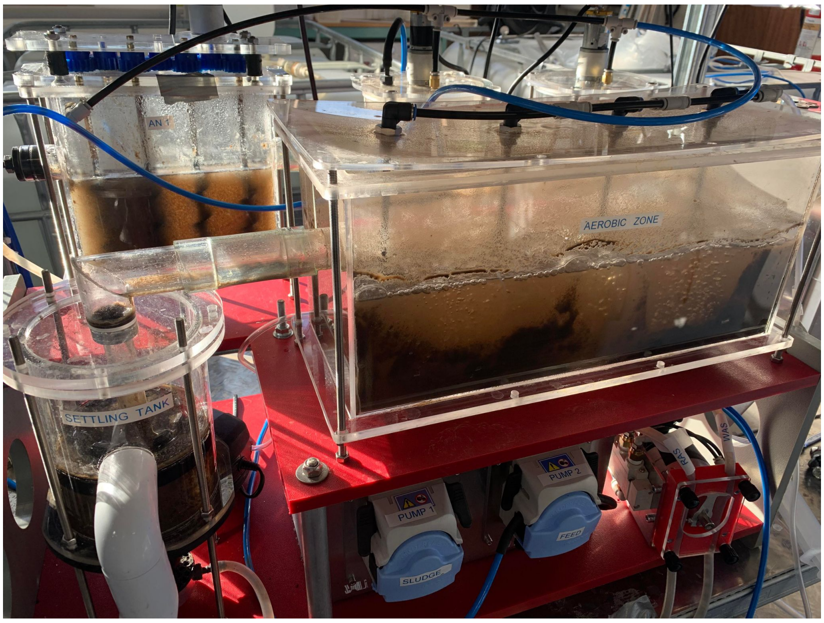

Figure 18: The picture shows how the pilot looks in Stage 2 after left to operate by its own. The anaerobic reactors are still diluted, but not as much as observed in Stage 1.


Figure 19: A close up of the settler in Stage 2.

Even with the changed pumping rate the sludge still had problems with settling. Sludge was also observed in the effluent during this stage. Figure 19 shows a close up of the settling tank. One hypothesis was that the sludge did not settle due to possible filamentous bulking in line with the observation in the aeration tank. It was noted that small gas bubbles were observed in the settler. To exclude the possibility that the bubbles were caused by anaerobic conditions in the settler the DO was tested. The DO in the settler was found to be 7 mg/L.

A batch test was performed during this stage, using sludge from the aerobic reactor. It is observed that this cause a disturbance in the pilot performance which takes at least two days to recover. Results provided from the pilot before it is recovered would be poor and not representable.

4.2.2 P – removal

It was still challenging to achieve a stable situation as the anaerobic reactors continues to become diluted. Table 12 shows the resulting P – removal in Stage 2. The removal increases during this stage, but the performance has still potential to become better.

Table 12: The table shows the P – removal in Stage 2.

Date [dd.mm.yyyy]	**Influent** [mg P/L]	**Effluent** [mg P/L]	**Removed** [mg P/L]	**% P-removed** [%]
29.03.2022	2.85	2.82	0.03	1.1
07.04.2022	3.70	3.16	0.54	15

4.2.3 Effluent sludge

Sludge is observed in the effluent in this stage. Table 13 shows the difference in TS and VS in and out of the pilot.

Table 13: The table shows the TS and VS found in the influent and effluent in Stage 2.

	TS [mg/L]	**VS [mg/L]**
Influent	450	159
Effluent	3468	1036

The amount of TS and VS out of the pilot is much higher than the amount in. The values for the effluent are almost the same as found for the aerobic chamber, that can be seen in Table 14.

4.2.4 SRT

As the situation in the pilot was still not stable the SRT was found while the pilot was supervised. The calculated SRT can be seen in Table 14. The same volume of WAS is assumed for this stage. The SRT calculated for the pilot in this stage is 3.6 days which is close to the SRT found at IVAR. The calculation does not take into account the TS and VS found in the effluent and can therefore be expected to be lower than what is calculated.

Table 14: The table shows the different SRT for both the whole pilot and for the aerobic reactor calculated with TS and VS for Stage 2.

Aerobic		**RAS**		**WAS**	**Pilot SRT**		**Aerobic SRT**	
TS_{AE} [mg/L]	VS_{AE} [mg/L]	TS_{RAS} [mg/L]	VS_{RAS} [mg/L]	V_{WAS} [ml]	$SRT_{p.TS}$ [days]	$SRT_{p.VS}$ [days]	$SRT_{AE.TS}$ [days]	$SRT_{AE.VS}$ [days]
3536	1168	6132	3056	580	7.4	4.9	5.5	3.6

4.2.5 SVI

The sludge settle properties in this stage is very good. IVAR reports to have an SVI < 100 and the sludge in the pilot provides an even better property. The SVI found in Stage 2 is shown in Table 15 and is equal to 34. This is much lower than what is reported by IVAR.

Table 15: The SVI found in Stage 2.

TS_{AE} [mg/L]	**V [mg/L]**	**SVI**
3536	120	34

4.2.6 Kinetic batch experiment

The batch experiment was performed with raw influent wastewater. This means that the wastewater does not have the same conductivity as the influent wastewater to the pilot due to the lack of seawater.

The batch experiment makes it possible to see if adding acetate, and thereby increase the available VFA for the PAOs, would increase the P – removal. The calculation for acetate added to the experiment can be found in Appendix 12. Figure 20 shows the result from the batch experiment. The batch experiment utilize the HRT calculated in Chapter *3.1.3 HRT.* The black line at 75 min indicates where the experiment goes from anaerobic to aerobic conditions. Tables with all parameters found in the experiment can be found in Appendix 13.

The plot shows the P – release and uptake are similar for both batches, with Batch 1 having a slightly better removal. The amount of P removed is respectively 53% for Batch 1, the control batch, and 43% for Batch 2, the batch containing acetate. This indicates that adding VFA as acetate to the solution will not help with the removal efficiency of the pilot. In 75 minutes the PAOs in Batch 1 are able to release 0.94 mg P/L, while they release 1.15 mg P/L in Batch 2. The batch with acetate has a slightly faster release rate. Batch 1 takes up 2.71 mg P/L in the 255 minutes long aerobic phase and Batch 2 takes up 2.53 mg P/L. Batch 1 shows therefore a faster uptake rate and get overall the highest removal efficiency between the two batches.

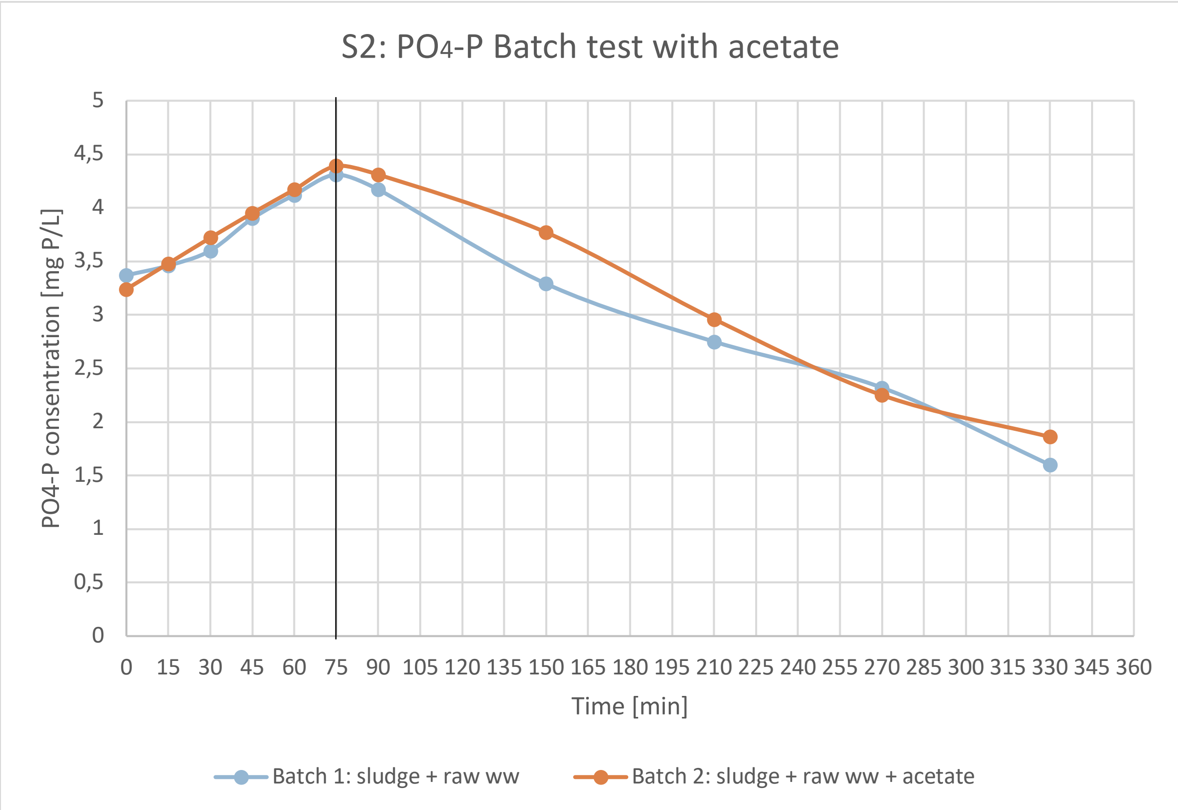

Figure 20: The plot shows the different PO_4-P concentration in a control batch VS a batch containing acetate.

Figure 21 shows the COD uptake during the experiment time. The plot shows that the COD at the start of the experiment period is higher in the batch without acetate. At the end of the experiment the COD concentration found in the two batches are the same. The remaining COD can be assumed to be more slowly biodegradable COD.

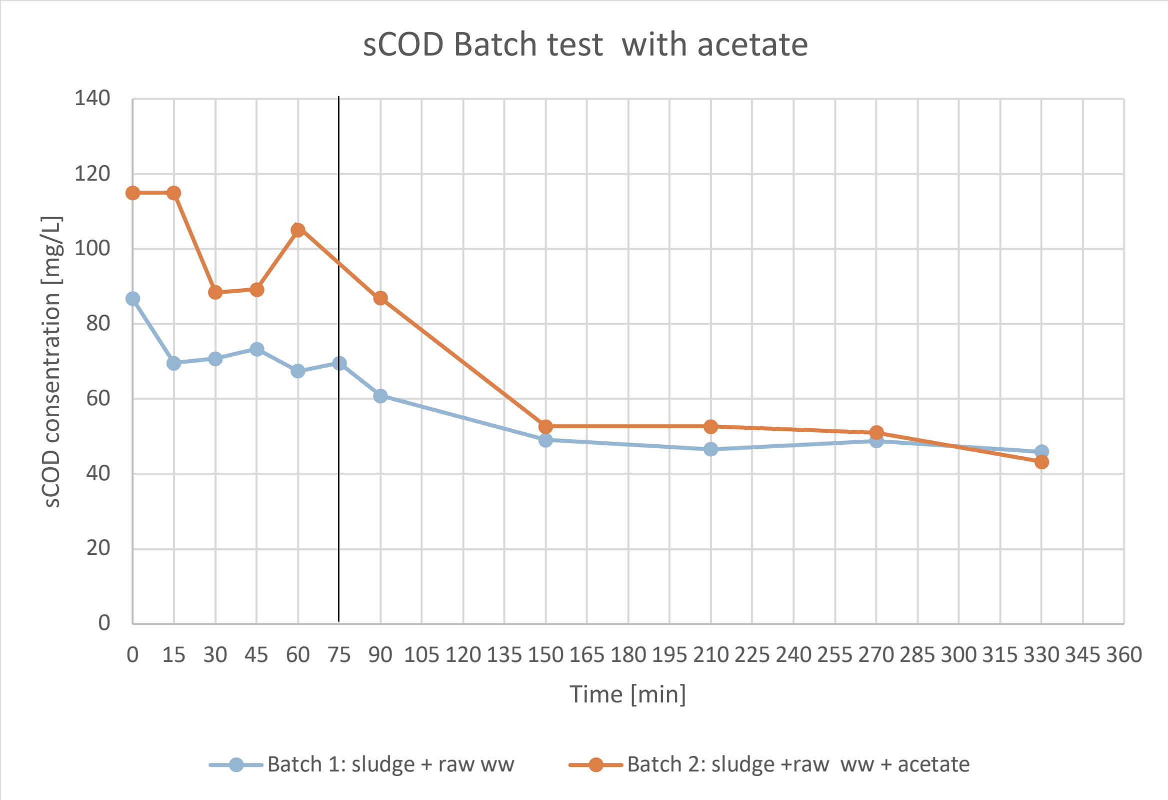

Figure 21: The plot shows the sCOD concentration in mg/L for a control batch VS a batch containing acetate.

4.2.7 Discussion

The changes that were implemented was not sufficient to overcome the operational challenges. The SVI for the sludge is very low, which means the sludge settles fast. This may increase the problem with settling in the aerobic chamber. More drastic measures to ensure turbulence in the aerobic reactor is in order.

Changing the RAS pumping did somewhat help to increase the concentration in An1, but the reactor is still highly diluted. It is suspected that the design at the bottom of the settler may be the cause for this inconvenience, as the construction of the inside is unknown. The design, together with a 90° angle and a narrow outlet may contribute to the diluted RAS flow. This hypothesis is grounded in observations which shows that by priming the sedimentation tank, problems related to dilution and sludge in the effluent decrease. Priming consists of manually running the pump at the highest speed for short periods. It is suspected that the sludge in the effluent is caused by the settler's lack of ability to remove sludge trough the RAS flow. As the SVI is really low it is unlikely that that challenges seen in the settling tank is related to filamentous bulking. The low SVI is contradictive to finding sludge in the effluent and is most likely caused by local problems in the settler.

The batch experiment showed that adding acetate to the solution did not help with the P – removal. Adding acetate is not considered ideal and it is therefore useful to know that it will not increase the P – removal in the pilot. The similar uptake and release pattern in the two batches may indicate that acetate is not the prefer type of VFA for the PAOs found in this solution. Literature states that although acetate is the model substrate for EBPR, experiments conducted with a VFA blend is found to be more favorable, especially if it contains propionate (Coats, et al. 2018). They continue to say that fermented RAS from side – stream configuration can achieve the same result as the blend. It is also observed that although the batch with acetate starts with a higher COD the two batches had the same COD concentration at the end of the experiment. A lot of the COD for Batch 2 is consumed in the anaerobic phase that may indicate the presence of GAOs. The experiment is also performed in room temperature where GAOs are likely to occur.

4.3 Stage 3: New settler and stirring mechanism in the aerobic chamber

To overcome the problems observed in Stage 2 a new settling tank and a stirring mechanism in the aerobic reactor is installed. The aim is to reduce the dilution of the RAS flow and ensure enough turbulence in the aerobic reactor to be able to operate the pilot at a stable condition. The intermittent RAS pumping and the pressure – based aeration system was kept for this stage.

Figure 22 compares the old and the new settler. The main difference is the design changes is the bottom outlet of the settler. The first settling tank had some unknow factors connected to its design of the bottom part as well as an unfavorable 90° angle at the connection to the RAS pump. The new design removed these uncertainties and gives a direct and much shorter connection to the RAS pump.

Figure 22: The picture shows the design of the old and new settling tank.

Figure 23 shows a picture of the stirring mechanism that is installed in the settling tank. The mechanisms are made to gently stir the sludge. Each of the stirrers turns in opposite direction of one another.

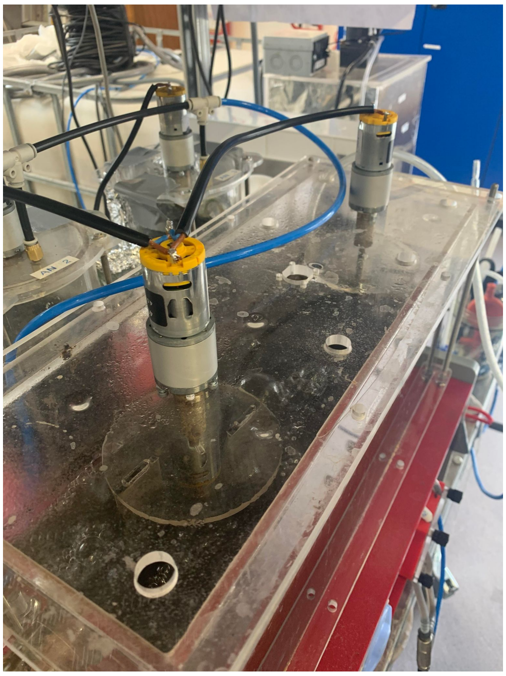

Figure 23: The picture shows the new stirrers in the aerobic chamber.

4.3.1 Performance

After installing the stirrers one can observe that the sludge is much more distributed in the pilot. Figure 24 shows a picture of the distribution of sludge after implementing the new changes. The pilot is now able to operate by its own without diluting the anaerobic reactors.

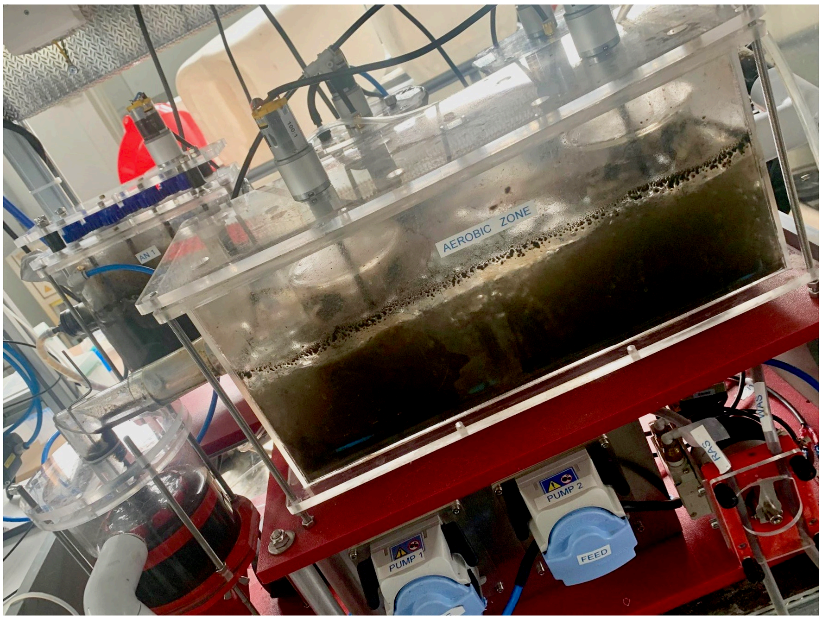

Figure 24: The picture shows how the pilot preforms during Stage 3.

For the first period of time the pilot was looking according to the expectations stated in *1.4 Hypothesis.* The pilot was operating with good sludge distribution, good settling and almost no sludge in the effluent. Figure 25 shows how the settler looked in this situation. Note that the water in the settler is rather clear, with only a few floating particles.

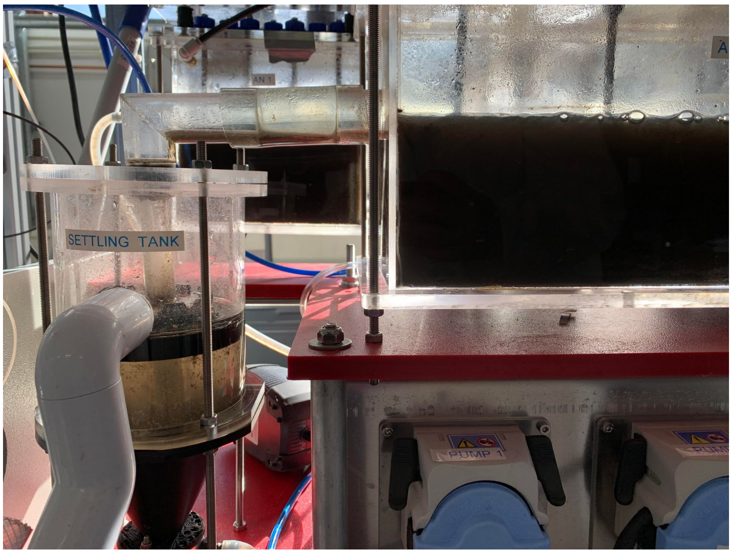

Figure 25: Picture of the pilot in operation at 23.04.22.

At 25.04.2022 some changes were observed in the pilot. Sludge started to accumulate up in the settling tank, which lead to sludge in the effluent. Figure 26 shows the settling tank after the sludge accumulation. Small bubbles were observed in the settler once again. The observation of bubbles may indicate the formation of gas. A reaction that can be found in wastewater treatment that can cause gas formation is denitrification. Tests were therefore conducted to determine if this could be the case.

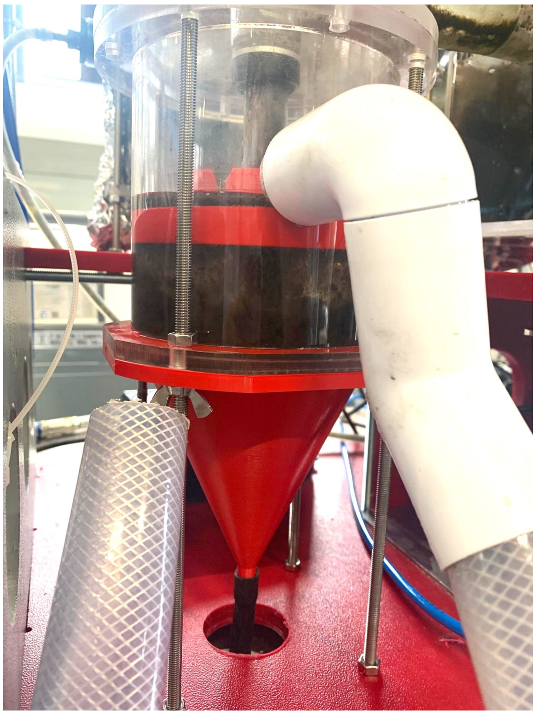

Figure 26: Picture of the pilot settling tank at 25.04.22. Sludge have started to accumulate.

4.3.2 P – removal

After implementing the changes, the pilot was able to operate with more stable conditions. This made it possible to have several datapoints for this stage. Table 16 shows the P – removal during this scenario. The influent and effluent concentrations as well as the percentage removed are plotted in Figure 27. The average P – removal in this stage is 41 %.

Table 16: The table shows the P – removal in Stage 3.

Date [dd.mm.yyyy]	Influent [mg P/L]	Effluent [mg P/L]	P-removed [mg P/L]	% removed [%]
19.04.2022	1.67	1.10	0.57	34
20.04.2022	1.64	1.05	0.59	36
21.04.2022	1.64	1.08	0.56	34
25.04.2022	3.85	1.70	2.15	56
26.04.2022	3.97	2.27	1.70	43

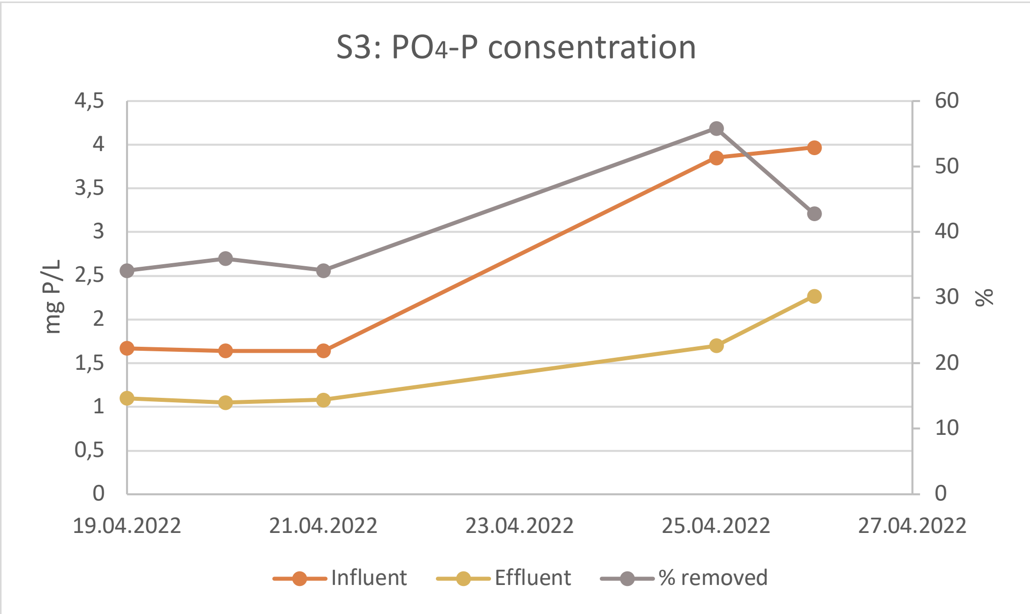

Figure 27: The plot shows the P – concentration in the influent and effluent in Stage 3 and the P – removal in %.

The pilot was able to have positive results during the hole period. The best removal is seen on 25.04.2022, with a 56% removal., which indicate a high potential of the pilot to mimic the IVAR condition. This result was surprising as it is coinciding with the first day of the sludge accumulation in the settling tank.

4.3.2.1 P/VS

The P/VS for Stage 3 is shown in Table 17. The P/VS is improved compared to the amount found in Stage 1 and continuous to improve during the course of this stage. The P/VS ratio increase despite the sludge accumulation in the settler.

Table 17: The table shows the P/VS in Stage 3.

Date [dd.mm.yyyy]	**PO_4-P** [mg P/L]	**Tot P** [mg P/L]	**VS** [mg /L]	**P/VS** [%]
21.04.2022	1.01	22.1	792	2.7
26.04.2022	2.42	56.6	1424	3.8

4.3.2.2 PAOs

Using Equation 4 it is possible to calculating the expected amount of PAOs found in the sludge. The result can be seen in Table 18.

Table 18: The table shows the calculated amount of PAOs in Stage 3.

Date [dd.mm.yyyy]	**PAOs** [mg/L]
21.04.2022	67
26.04.2022	172

4.3.3 COD consumption

Figure 28 and Table 19 shows the difference in COD level in and out of the pilot. As seen in Chapter *2.6.2 Operation parameters at IVAR* the real treatment plant had an influent sCOD concentration between 31 – 136 mg/L. The influent COD concentration into the pilot is between these values. It can be assumed that the amount of readily biodegradable COD in the influent is equal to the difference in COD level between the influent and the effluent.

Table 19: The sCOD consumption in the pilot in Stage 3.

Date [dd.mm.yyyy]	**Influent** [mg/L]	**Effluent** [mg/L]	**COD removed** [mg/L]	**% removed** [%]
19.04.2022	54.1	47.4	6.7	12
20.04.2022	50.5	38.1	12.4	25
21.04.2022	49.4	32.6	16.8	34
22.04.2022	117	46.5	70.5	60
25.04.2022	104	41.5	62.5	60
26.04.2022	111	42.2	68.8	62
27.04.2022	93	46.4	46.6	50
28.04.2022	115	65.7	49.3	43
29.04.2022	82.9	40.6	42.3	51

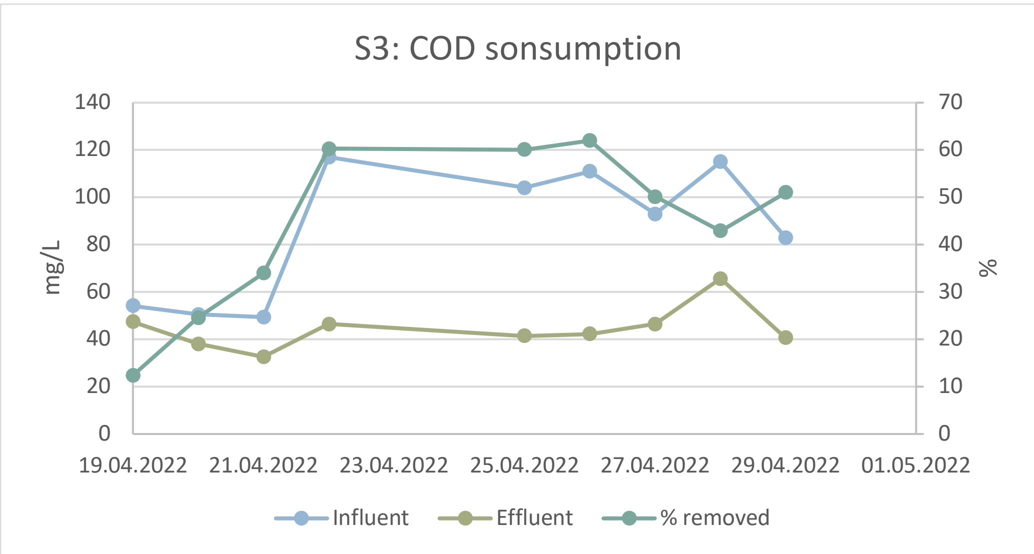

Figure 28: The plot shows in the influent and effluent sCOD in the pilot in Stage 3.

It is observed that the amount of COD removed are similar within the same batch of influent wastewater. The COD level in the influent wastewater also decrease over time within a batch. This can indicate COD consumption in the influent container.

4.3.3.1 COD/P – ratio

IVAR report to have a COD/P – ratio between 17 – 33 mg/mg. The COD/P – ratio found in the pilot is inside this interval with values reaching from 23 – 32 mg/mg.

Chapter *2.4.3 COD/P ratio* describes how the COD/P – ratio will affect the PAO/GAO competition in the treatment plant. GAOs will be more prominent when the COD fraction in the wastewater is low while the PAOs will be found at higher ratio. It is recommended that the value should be lower than 50:1 and that the best P – removal can be found between 15:1 – 25:1 (Wang, et al. 2019). The values shown in Figure 29 is higher than the recommended interval, but still lower than 50:1. On the other hand, not all of the COD measured is rbCOD. Based on the effluent COD around 40 – 60 mg/L of the COD is slowly biodegradable COD that cannot be utilized by PAOs or other organisms in the pilot with this HRT without being hydrolyzed.

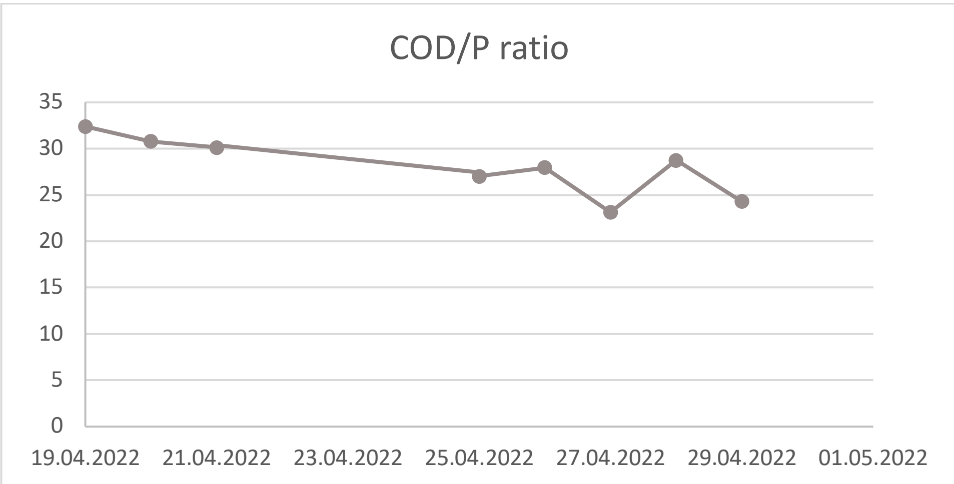

Figure 29: The COD/P ratio found in Stage 3.

4.3.4 Denitrification

It was suspected that the accumulation of sludge and the formation of bubbles observed in the settling tank was caused by denitrification in the settler. A sample was taken, which confirmed denitrification in the pilot. The result of the sample can be seen in Table 20.

Table 20: The denitrification found in Stage 3.

NH_4-N		NO_3-N				
Influent [mg N/L]	Effluent [mg N/L]	Influent [mg N/L]	Effluent [mg N/L]	Nitrified [mg N/L]	Denitrified [mg N/L]	% denitrified [%]
33.9	14.2	0.323	10	19.7	9.7	49

4.3.5 pH and DO in the aerobic reactor

Because of the suspicion of filamentous growth from earlier stages, the pH and DO of the aerobic reactor was monitored. The average temperature in the aerobic reactor during this period was 20.8°C. The variation can be seen in Table 21. The pH and DO do not seem to correlate to P – removal or the sludge found in the effluent in any way.

Table 21: The pH and DO found in the aerobic chamber during Stage 3.

Date	pH	DO
08.04.2022	7.60	4.80
12.04.2022	7.54	4.44
15.04.2022	7.61	5.47
19.04.2022	7.60	6.55
20.04.2022	7.66	6.04
22.04.2022	7.67	2.98
24.04.2022	7.90	7.00
25.04.2022	7.80	5.65
26.04.2022	7.93	4.91
27.04.2022	7.71	5.62
28.04.2022	7.60	6.40
29.04.2022	7.50	5.46

4.3.6 Effluent sludge

After 25.04.2022 sludge was observed in the effluent. Table 22 compares the solids in and out of the pilot. The amount of TS and VS is less than what was measured in Stage 2.

Table 22: The TS and VS found in the influent and effluent during Stage 3 after accumulation in the settler.

Influent	Date	TS	TSS	VS	VSS
	25.04.2022	2394	76	372	66
	26.04.2022	2430		500	
Effluent	Date	TS	TSS	VS	VSS
	25.04.2022	2440	48	396	48
	27.04.2022	2516		340	

4.3.7 SRT

The SRT for Stage 3 can be seen in Table 23. In this stage the SRT has become high. The result is more reliable than earlier stages because of stable operations. The calculated SRT gives an indication of the sludge age. However, the formula used is neglecting the effect of sludge in the effluent. As sludge is observed in the effluent at the time where the SRT samples were taken the SRT is expected to be lower, as a larger sludge volume is removed.

The SRT has not been increased by intention. The control panel of the pilot has shown to be easily affected by power cuts, and changes such as speed of the rotation in the anaerobic rectors has been observed after these events. Fortunately, the power cuts have not affected the pumping rate for the influent flow or the RAS flow.

Table 23: The SRT found in the whole pilot and in the aerobic chamber based on VS and TS in Stage 3.

Aerobic		**RAS**		**WAS**	**Pilot SRT**		**Aerobic SRT**	
TS_{AE} [mg/L]	VS_{AE} [mg/L]	TS_{RAS} [mg/L]	VS_{RAS} [mg/L]	V_{WAS} [ml]	$SRT_{p.TS}$ [days]	$SRT_{p.VS}$ [days]	$SRT_{AE.TS}$ [days]	$SRT_{AE.VS}$ [days]
3732	1424	6488	3560	264	16.12	11.21	11.98	8.33
3164	884	4676	2000	273	18.34	11.98	13.63	8.90

4.3.8 SVI

The settling properties were also tested in this situation. The SVI can be seen in Table 24. The SVI found was not as low as in Stage 2, but still less than 100, which is good.

Table 24: The SVI for Stage 3.

TS_{AE} [mg/L]	V [mg/L]	SVI
3732	360	96

4.3.9 Kinetic batch experiments

Three batch experiments were performed during this stage. The experiments and their differences are listed in Table 25.

Table 25: The table shows the batch experiments that were performed during Stage 3, the differences between the experiments and the appendix where their results can be found.

Date	Batch 1	Batch 2	Wastewater	Appendix
21.04.2021	Control batch: Sludge + ww	1h 23 min fermented sludge + ww	Raw influent wastewater	Appendix 14
26.04.2021	Control batch: sludge + ww	1h 23 min fermented sludge + ww	Container influent ww	Appendix 15
27.04.2022	1h 23 min fermented sludge + ww	Sludge + ww + acetate	Container influent ww	Appendix 16

4.3.9.1 Control batch VS Fermented batch

The experiments with fermented sludge was performed to see how the fermentation in An1 could affect the P – removal in the pilot. The experiment conducted at 26.04.2021 is the most representative as it uses the influent wastewater as the pilot and is compared to a control batch. The resulting P – release and uptake from the experiment can be seen in Figure 30.

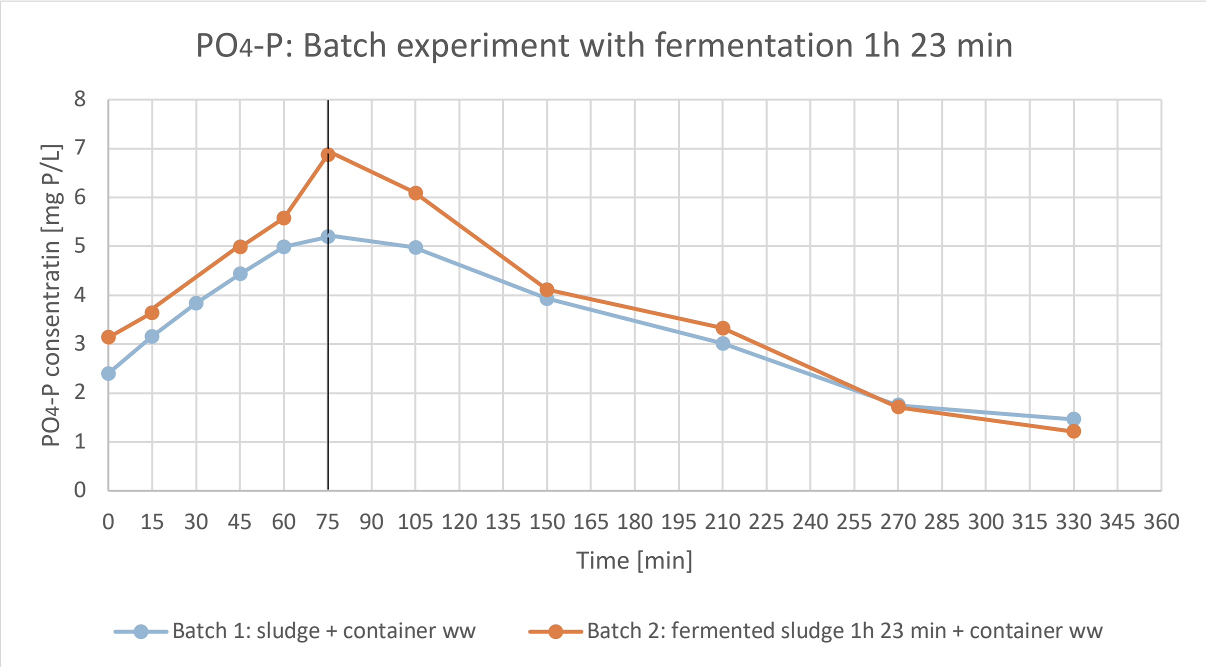

Figure 30: The plot shows a control batch VS a batch with fermented sludge. Experiment executed at 26.04.2022.

The Batch 2, fermented batch, had a higher P – release (3.73 mg P/L) in the anaerobic phase and a higher uptake (5.66 mg P/L) in the aerobic phase than the control batch which released 2.79 mg P/L and took up 3.73 mg P/L. The total PO_4 – P removed in Batch 1 was 0.94 mg P/L or 39 % while the P – removed in Batch 2 was 1.93 mg P/L which entails to 61 %. This indicates that the fermentation is improving the P – removal process. Compared to the experiment done in Stage 2 with acetate, this experiment indicates that the fermentation may produce other VFAs that the PAOs may preferer.

4.3.9.2 Diluted batch VS undiluted batch

The concentration in P varies in the influent wastewater. Figure 31 shows the result for the fermented batches for experiment 21.04.2022 and 26.04.2022. For 21.04.2022 the wastewater was diluted due to snow melting and had therefore low concentration of PO_4-P at the start point. IVAR has typically much lower PO_4-P values than what is found in Trondheim and can therefore expect result closer to what is found in Experiment 21.04.2022. The plot shows that the two concentrations follows the same uptake and release pattern.

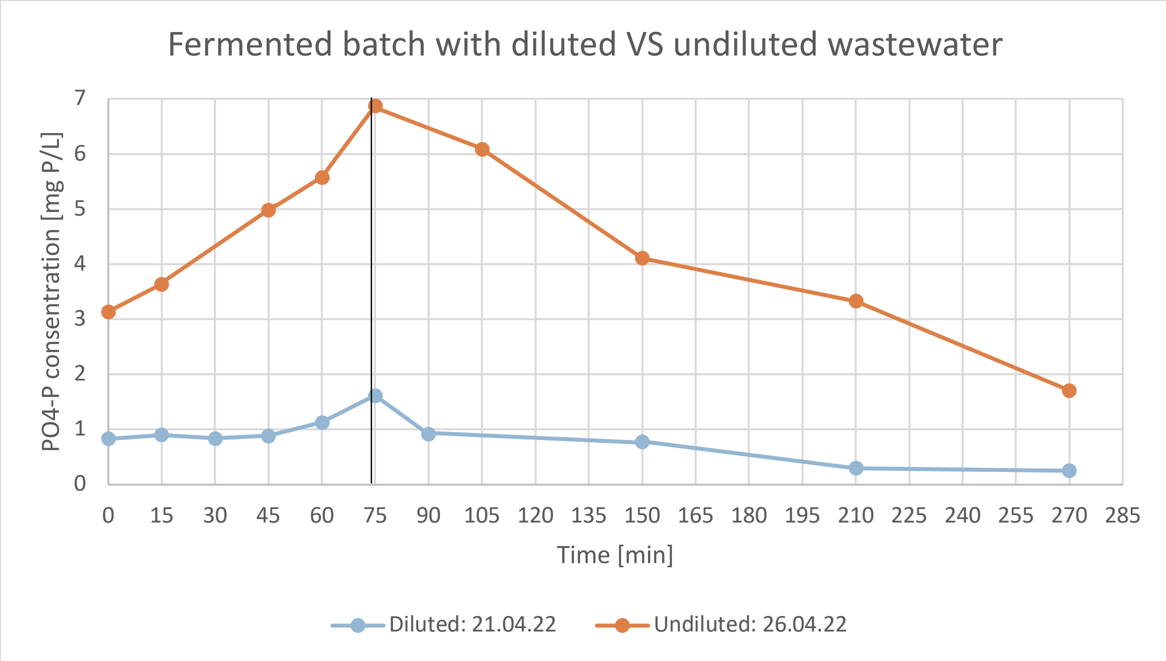

Figure 31: The plot shows the PO_4-P concentration for a batch experiment with diluted wastewater and fermented sludge (executed at 21.04.22) compared to a batch with not diluted wastewater and fermented sludge (executed at 26.04.22).

The fermented diluted sample had a P – removal equal to 69 % and the fermented undiluted a removal equal to 61 %.

4.3.10 Discussion

The new configurations made the pilot able to operate in more steady conditions. This allowed for a higher P – removal than seen in the earlier stages.

The most unexpected result in this stage was that the best P – removal was found when sludge started to accumulate in the settler. The accumulation was suspected to be caused by denitrification in the settler, as small bubbles were observed. Tests proved that denitrification takes place in the pilot, which supports the assumption. The denitrification can be a result of the increased sludge age. The pilot is also operated at room temperature. Increased temperatures make it possible for nitrification to occur even at lower sludge age. Even though the settler is supposed to be aerobic it is possible that the conditions turns anaerobic when the sludge stays in the settler for too long. With the presence of nitrate or nitrite denitrification can occur.

The results show that the settling properties of the sludge has become less good, as the SVI has increased. Studies have shown that the sludge gets poorer settling properties when SRT increases (Onnis-Hayden, et al. 2019). However, the SRT is still lower than 10 days and an SVI at 96 is considered good.

The P – content in the sludge have increased. This may also help to increase the P – uptake in the pilot. Studies has shown that increased SRT can result in increased P – content in biomass (Onnis-Hayden, et al. 2019). SRT less than 10 days are also said to favor the growth of PAOs over GAOs.

The batch test shows that the pilot has potential for good P – removal. The fermented batches were able to remove more P than the control batches, indicating that the side – stream configuration may contribute to better P – removal in the pilot. Fermentation of RAS should be able to produce a blend of VFA, giving the PAOs several options to choose from. The removal efficiency in the diluted batch experiment was 69%, while it was 61% for the undiluted. This may indicate that the potential removal in the pilot is not affected by the inlet concentration. GAOs have shown to be more prominent when the wastewater is more diluted, however this do not seem to be the case, as the diluted batch manage to have the best P – removal.

4.4 Stage 4: Increase of WAS flow and increase VFA in influent wastewater

To avoid the floating sludge in the settling tank the WAS flow is increased, thereby reducing the sludge age and hopefully the challenges related to this.

As the floating sludge is suspected to be related to the denitrification in the settler an attempt to move the denitrification from the settler to An2 is made. This is done by feeding acetate to the influent container. It is also suspected that anaerobic conditions as well as consumption of COD occurs in the influent container as the same wastewater is kept for one week at the time. Acetate was added to the container at 10.05.2022 in order to reach a COD level in the influent equal to 100 mg/L. The calculations for the amount added can be found in Appendix 17. At

12.05.2022 a new batch of influent wastewater was prepared, and additional acetate was added in order to reach a concentration equal to 200 mg/L. The calculations can be seen in Appendix 18. As acetate was added to the solution in order to increase the COD, the dilution was no longer needed. The new influent wastewater composition is listed in Table 26.

Table 26: Influent wastewater composition after adding acetate.

Wastewater [L]	**Seawater** [L]	**$CH_3COONa * 3 H_2O$** [g]
940	60	231

4.4.1 Performance

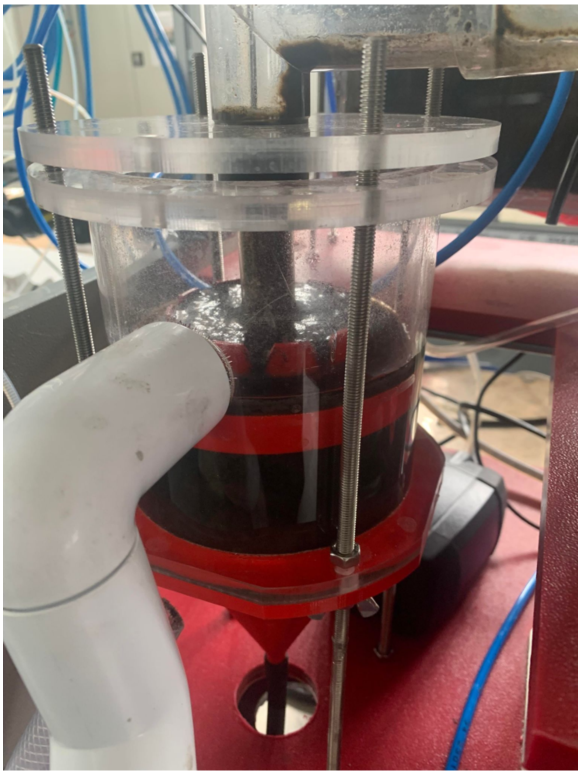

Figure 32: The picture shows the accumulation of sludge in the settler in Stage 4.

The pilot is able to operate in a stable condition where the sludge is distributed equally good as in Stage 3.

The changes implemented in Stage 4 was to handle the problems with sludge accumulation in the settling tank that occurred in Stage 3. However, the amount of floating sludge in the settler do not decreese, and neither does the amount of floating sludge found in the effluent. Figure 32 shows a picture of the settling tank with a thick layer of floating sludge at the surface.

4.4.2 P – removal

Stage 4 did also have a stable operation and was able to remove phosphorus. The removal is listed in Table 27 and the influent and effluent concentrations are plotted in Figure 33. The average P – removal is 42 %, which is almost the same as found in Stage 3. From earlier batch experiments it has been observed that increasing the COD level by adding acetate did not increase the P – removal. The resulting P – removal in the pilot after adding acetate support this observation. The highest P – removal observed during the experiment period is observed at 10.05.2022 with a removal equal to 69%. The sample of the P – removal at 10.05.2022 was not affected by the increased COD in the influent as it was taken before adding acetate.

Table 27: The table shows the PO_4-P concentration in the pilot at Stage 4.

Date [dd.mm.yyyy]	Influent [mg P/L]	Effluent [mg P/L]	P-removed [mg P/L]	% removed [%]
10.05.2022	3.84	1.19	2.65	69
11.05.2022	3.19	2.05	1.14	36
12.05.2022	4.23	3.01	1.22	29
16.05.2022	5.95	3.97	1.98	33

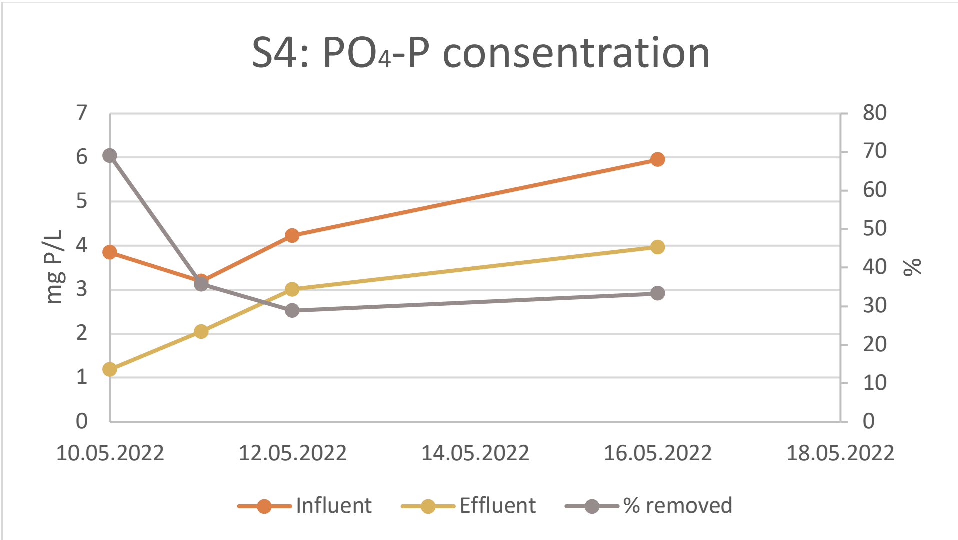

Figure 33: The plot shows the influent and effluent PO_4-P concentration in the pilot and the P-removal in % at Stage 4.

As the settler was filled with sludge it was of interest to see how the PO_4-P concentration in the effluent was compared to PO_4-P measured in the aerobic chamber. Because of the amount of sludge seen in the settler the PO_4-P concentration was expected to increase. The expectation was based on result from IVAR that support secondary release of P in the settler (Lilleland 2019). Table 28 shows the effluent PO_4-P concentration compared to the the aerobic concentration the same day. The data contradict the assumption and indicates PO_4-P uptake in the settling tank.

Table 28: The PO4-P concentration in the effluent and the aerobic chamber in Stage 4 at 11.05.2022.

	Effluent	**Aerobic**
PO_4-P [mg P/L]	2.05	3.08

4.4.3 COD consumption

The COD consumption found in the pilot is shown in Table 29 and plotted in Figure 34. The acetate was added for the first time at 10.05.2022 to the influent container. The sample taken that day will not be affected as it was taken before adding the acetate to the influent wastewater. At 12.05 acetate was added again.

Table 29: The sCOD consumption in the pilot in Stage 4.

Date	Influent	Effluent	COD removed	% removed
10.05.2022	77.7	49.4	28.3	36
11.05.2022	95.1	44.2	50.9	54
12.05.2022	104	30.6	73.4	71
16.05.2022	149	53.3	95.7	64

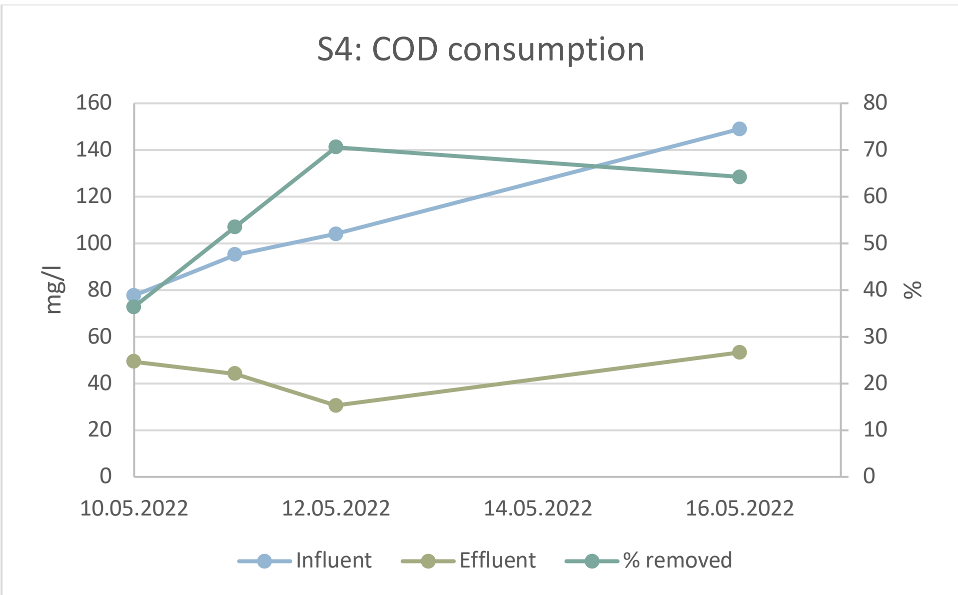

Figure 34: the sCOD concentration in the influent and effluent and the % removed in Stage 4.

4.4.3.1 COD/P

Figure 35 shows the influent COD/P ratio for Stage 4. Most of the measurements are inside the recommended values for good P – removal: 15:1 – 25:1 (Wang, et al. 2019), and all are below 50:1. The highest value is 30:1, which correspond with a P – removal equal to 35%.

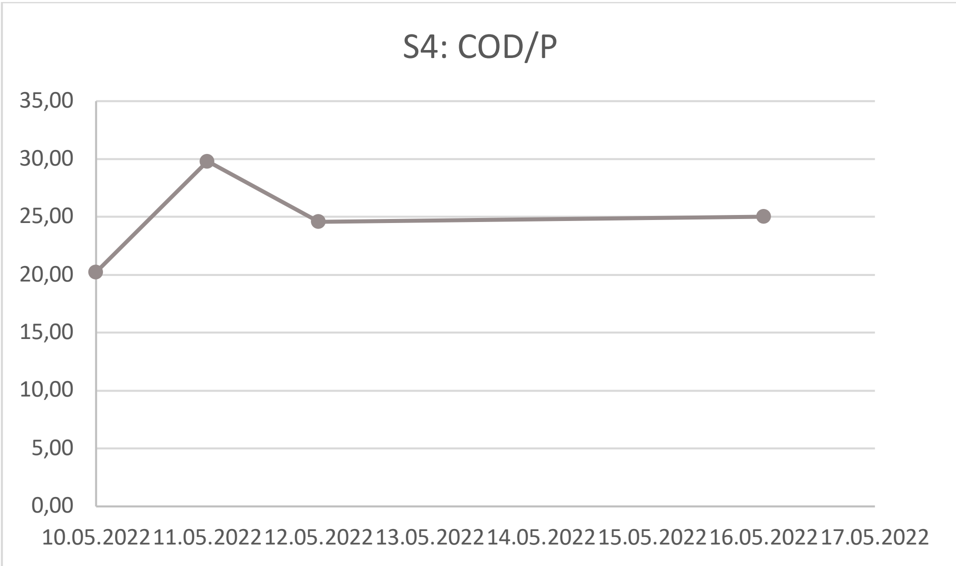

Figure 35: The COD/P ratio in Stage 4.

4.4.4 Denitrification

As denitrification in the pilot is observed, it is monitored in this stage, and the results are shown in Table 30. It can seem like the nitrification decrease when adding COD to the pilot. It does also seem like the denitrification is decreasing after adding COD, however the two last points would be needed to verify that. Less nitrification can happen when COD is added and the SRT is decreased.

Table 30: The denitrification in the pilot in Stage 4. The two last points do not include denitrification because of lack of analyzing kits.

	NH_4-N		NO_3-N				
Date [dd.mm.yyyy]	**Influent** [mg N/L]	**Effluent** [mg N/L]	**Influent** [mg N/L]	**Effluent** [mg N/L]	**Nitrified** [mg N/L]	**Denitrified** [mg N/L]	**% Denitrified**
03.05.2022	24.5	12.8	0.307	10.3	11.70	1.40	12
05.05.2022	33.7	10.6	0.256	12.8	23.10	10.30	45
09.05.2022	24.5	1.14	0.292	12.7	23.36	10.66	46
10.05.2022	25.5	0.134	0.275	14.2	25.37	11.17	44
11.05.2022	19.8	0.202	0.221	13.7	19.60	5.90	30
12.05.2022	13.6	1.36	0.455	10.6	12.24	1.64	13
13.05.2022	46.4	25.3			21.10		
16.05.2022	40.1	22.3			17.80		

It is possible to calculate the minimum sludge age where nitrification will occur given the temperature of the wastewater (Henze, et al. 2008). The average aerobic temperature is ≈ 20 °C. The minimum sludge age for nitrification is calculated in Appendix 19 to be 2.6 days. As calculated the minimum SRT for nitrification at this temperature is very low, which indicates that nitrification can easily occur.

4.4.5 Sludge in effluent

Because of the floating sludge in the settler, sludge is found in the effluent. Table 31 shows the TS and VS measured in the effluent in this stage. In Figure 32 a layer of sludge that looks very thick on the surface of the settler. However, the TS is close to what was found in Stage 3, but the VS has increased.

Table 31: The table shows the TS and VS measured in the effluent in Stage 4.

	TS [mg/L]	**VS [mg/L]**
Effluent	2456	648

4.4.6 SRT

The SRT for this stage is shown in Table 32. For Stage 4 it is 3.4 days. The sludge age is now much reduced to what was found in Stage 3, and closer to what is used at IVAR which is 3.3 days. However, since Equation 7 neglect the sludge in the effluent the real sludge age is possibly less than what is calculated in Table 32.

Table 32: The table shows the SRT for the whole pilot as well as the aerobic SRT calculated using both TS and VS for Stage 4.

Aerobic		**RAS**		**WAS**	**Pilot SRT**		**Aerobic SRT**	
TS_{AE} [mg/L]	VS_{AE} [mg/L]	TS_{RAS} [mg/L]	VS_{RAS} [mg/L]	V_{WAS} [ml]	$SRT_{p.TS}$ [days]	$SRT_{p.VS}$ [days]	$SRT_{AE.TS}$ [days]	$SRT_{AE.VS}$ [days]
2964	872	5589	2814	500	7.9	4.6	5.8	3.4

4.4.7 SVI

The SVI has been reduced since Stage 3. Table 33 shows that the SVI found in Stage 4 is equal to 77.

Table 33: The calculated SVI for Stage 4.

TS_{AE} [mg/L]	V [mg/L]	SVI
3104	240	77

4.4.8 Discussion

The measures implemented was meant to reduce the sludge age, and thereby reducing problems related to that. After decreasing the sludge age, the SVI was reduced, implying that the settling properties of the sludge should have become better. The better settling properties did not help with the floating sludge, as it is still observed in the settler. This implies that the problems in the settler is not related to the settling properties in the sludge but is found locally in the settler. According to the calculation done in Chapter *4.4.4 Denitrification* the sludge age need to be less than 2.6 days to avoid nitrification when the pilot is operating in room temperature. This is less than the 3.4 days that the pilot SRT is calculated to in Stage 4. IVAR do not experience nitrification and denitrification, which may be caused by the fact that they operate the treatment plant with a lower temperature on the wastewater.

It would be expected that the amount of sludge in the settler would lead to secondary P – release, and thereby decrease the efficiency of the P – removal. This do not seem to be the case. The average P – removal is the same as seen in Stage 3. One datapoint showing the PO_4-P concentration for both aerobic reactor and effluent indicates that there is a reduction in P in the settler as well. This may be caused by denitrifying PAOs (DPAOs). DPAOs are PAOs that can use nitrogen compounds (nitrate and/or nitrite) as electron acceptors in an anoxic zone (Lanham, et al. 2018). They have the ability to remove both nitrogen and phosphorous simultaneously. Studies have showed that DPAOs have the ability to remove 4–5 g NO_3^--N per g P without utilizing COD and produce 20 – 30% less sludge (Lee and Yun 2014). As the uptake from these are varying a lot, they are usually not considered for design purposes (Henze, et al. 2008). Even if the denitrification in the settling tank is able to provide DPAOs it is still the issue with the sludge in the effluent. The sludge contains high amount of phosphorus that will be released as PO_4-P in a recipient and the effect of P – removal will be lost.

Nitrification is also not desirable in the EBPR treatment process as nitrate can work as an electron acceptor, making it possible for the OHOs to utilize rbCOD in the anaerobic reactor when nitrate follows the RAS flow (Henze, et al. 2008, 162). This will increase the competition between OHOs and PAOs in the anaerobic zone and thereby reducing the corresponding P – removal of the pilot. In order to reduce problems related to nitrification either the sludge age or the temperature need to be reduced.

Temperature is a parameter that is likely to speed up processes in the biomass, it is therefore also likely to affect other parameters in the pilot. GAOs are said to be more dominant at temperatures closer to 20 °C which means that the P – removal can benefit from reducing the temperature. As long as the pilot stays in room temperature, it will be impossible to evaluate the effect of the operational parameters from IVAR or optimize the process in a way that is compatible to the real treatment plant.

5 Further work

The further work has to focus on two things: to solve the operational challenges that occurs in the pilot and to optimize the EBPR process for the pilot. A lot of the challenges seen in the pilot operation that is not solved in this thesis is connected to temperature. As long as the pilot is operated in room temperature it will not be able to get the same conditions as found at IVAR. A focus point in the further work need to be how to operate the pilot at temperatures similar to what is found at IVAR.

Another factor that may influence the pilot operation is the age of the influent wastewater. The pilot was operated with wastewater that was up to a week old. Compensating for the freshness by adding COD in Stage 4 did not improve the operational challenges. The possibility of changing the water more frequently must therefore be examined.

The results in this thesis indicate that the operational parameters used at IVAR may not be optimal to reach an effluent PO_4–P concentration of 0.5 mg P/L. The further work must also look in to changing the operational parameters for optimization. This could include changing the RAS flow, the SRT or other parameters.

6 Conclusion

After a period of trouble shooting it was possible to get the pilot to get a steady operation. It was expected that clogging would be a problem because of the high SVI combined with small dimensions, but no incidents of trouble due to this occurred during the experiment period. However, the high SVI did cause a major problem in the operation of the pilot, as the sludge settled in the aerobic reactor. The settling in the aerobic zone was solved by installing mechanical stirrers in the aerobic reactor that ensured turbulence. This led to a better distribution of sludge in the lab – scaled pilot. When in steady state the pilot was able to achieve an average P – removal of 42% and the maximum P – reduction seen in the experiment period was 69 %. Batch experiments also show a high potential for P – removal. These experiments favored fermented sludge over adding acetate to the pilot and indicated great potential for P – removal with optimization. EBPR has a potential to reach effluent PO_4-P concentration down to 0.5 mg P/L. As this was not achieved during the experiment period it may indicate that the operational parameters used are not optimal. Further work on optimizing the process need to be done.

The pilot was able to operate with the same influent COD/P ratio as found in IVAR, have the same SRT and the same scaled down influent and RAS flow. Some changes, like changing to intermittent RAS flow was made, as the flow became very small when scaled down. Because the pilot is placed inside the lab the average wastewater temperature was higher than what is found at IVAR. This caused some operational challenges that is not found at the real treatment plant. A higher temperature affects all biological processes and speed up the reaction rate. Due to the high temperature the pilot started to perform nitrification and denitrification. It was expected that the pilot was going to have less problems in the settling tank than IVAR. Because of the denitrification, production of nitrogen gas caused a problem with floating sludge in the settler. This led to sludge in the effluent flow. Surprisingly the data do not indicate PO_4-P secondary release in the settler after accumulation of sludge, unlike what was found at IVAR. Instead it may seem that the pilot has denitrifying PAOs in the settler. But the effluent containing sludge with high P – concentration is a problem. Operating the pilot with a lower temperature could be expected to solve the challenges connected to the settling tank and should be done for the next stage of the project.

Figures

Tables

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