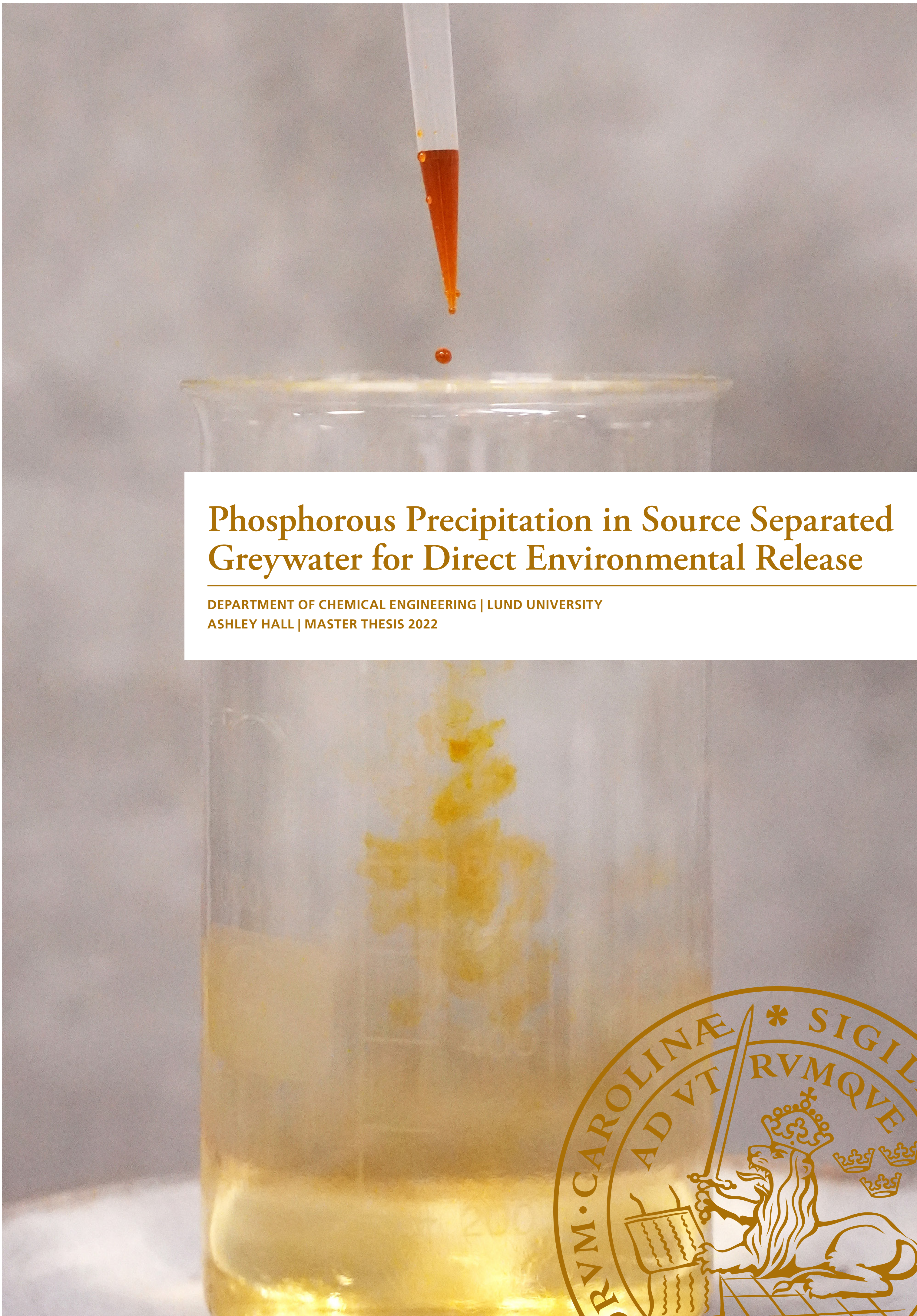


Phosphorous Precipitation in Source Separated Greywater for Direct Environmental Release

DEPARTMENT OF CHEMICAL ENGINEERING | LUND UNIVERSITY
ASHLEY HALL | MASTER THESIS 2022

Phosphorous Precipitation in Source Separated Greywater for Direct Environmental Release.

by

Ashley Hall

Master Thesis number: 2022-04

Water and Environmental Engineering
Department of Chemical Engineering
Lund University

May 2022

Supervisor: **Åsa Davidsson**
Co-supervisor: **Hamse Kjerstadius**
Examiner: **Michael Cimbritz**

Picture on front page: Iron-based coagulant being added to tap water. Photo by Hilde Skar Olsen.

Postal address
Box 124
SE-221 00 Lund, Sweden
Web address
http://www.lth.se/chemeng/

Visiting address
Naturvetarvägen 14

Telephone
+46 46-222 82 85
+46 46-222 00 00

Postal address
Box 124
SE-221 00 Lund, Sweden
Web address
http://www.lth.se/chemeng/

Visiting address
Naturvetarvägen 14

Telephone
+46 46-222 82 85
+46 46-222 00 00

Preface

Thank you to my supervisors Hamse Kjerstadius and Åsa Davidsson for their support and guidance over the course of the project as well as giving me the independence and space to make mistakes and develop academically. Thank you to Michael Cimbritz for supplementing their knowledge, acting as examiner, and being confident in my abilities even if I was not. Thank you to Lindell Ormsbee for being my biggest cheerleader from across an ocean, his support has given me the confidence in myself and my knowledge to pursue my passions. Thank you to Per Falås for being a huge support during laboratory work and always being there to answer any questions. Thanks to Ellen Edefell and Maria Takman for talking through life with me and encouraging me through the project. Thanks to Lina Lennklev and Elin Nilsson for driving me to collect samples and being the most helpful office mates one could hope for. Thank you to Mehrzad Ghassemi for being there to exchange ideas and compare results as well as inspiring me with his drive and success in Swedish in the workplace. Thank you to Tobias Erlström, Zeinab Nasser and Anita Korba with help developing my professional writing skills in Swedish, and even some English along the way.

Thank you to the staff at Öresundsverket and RecoLab for helping with sample collection, providing historical data used in this report, and helping to fund this project. Thank you to the entire Chemical Engineering department at LTH for being so amazing and making the department a fun and enjoyable place to come during my thesis. If I have to spend so much time somewhere, I'm happy it is here with y'all.

Summary

As our understanding of the impact humans have on the environment changes, so too do the mitigation strategies we employ to prevent it. One major source of anthropogenic pollution is wastewater effluent. A shift towards source separation of wastewater into different streams in recent years has opened a door to tailor treatment to specific types of water. The largest proportion of domestic wastewater is classified as greywater, accounting for 70% of the volume but containing roughly 30% of the contamination. Low influent concentrations of nutrients, like phosphorus, can result in lower effluent concentrations with similar amounts of chemical addition. While biological and physical treatments are possible, chemical precipitation remains a simple way of achieving extremely low phosphorous concentrations. Chemical precipitation also has the ability to remove nonreactive phosphorous through sweep coagulation. Because of the relative novelty of source separation on a larger scale, not much literature exists on the use of phosphorous precipitation in greywater. The placement, dosing, chemicals, and limits of removal of total phosphorous were tested using greywater from RecoLab in Helsingborg, Sweden. Greywater exiting the biological stage of treatment required lower doses of coagulant and was capable of reaching lower residual total phosphorous concentrations, chemical oxygen demand, and turbidity compared to influent greywater. Depending on treatment plant layout, precipitation within the biological stage can remove or diminish the risk of precipitating too much phosphorous, which can lower the efficacy of the biological step. Of the two compounds considered, the aluminum-based coagulant (PAX-XL60, Kemira) achieved better removal rates than the iron based one (PIX-111, Kemira) in the ranges of concentrations most commonly used at traditional wastewater treatment plants. Removal of phosphorous below a detection limit of 0.05 mg P/L was achieved with 15 mg Al^{3+} /L or 45 mg Fe_{tot} /L in biologically treated greywater while minimum concentrations of 0.16 mg P/L and 0.14 mg P/L were achieved in influent greywater by adding 17 mg Al^{3+} /L and 36 mg Fe_{tot} /L, respectively.

Sammanfattning

Allt eftersom vår förståelse om vår egen miljöpåverkan förändras, så förändras också begränsningsstrategierna vi använder för att förhindra och motverka dem. En viktig källa till antropogena utsläpp är avloppsvatten eftersom det innehåller patogener, näringsämnen, och mikroföroreningar. Ett skifte mot källsorterat avloppsvatten under de senaste åren har öppnat dörren för att anpassa och fokusera reningen för vatten från olika ursprung. Gråvatten utgör den största delen av avloppsvattnet, som är 70% av volymen men innehåller bara drygt 30% av föroreningarna. Låga koncentrationer av näringsämnen, som fosfor, kan resultera i lägre utkommande koncentrations med lika mängd kemisk tillsats. Medan biologisk och mekanisk rening är möjlig, är kemisk fällning enklare att implementera för att uppnå mycket låga fosforkoncentrationer. Kemisk fällning har också förmågan att avskilja ännu mer icke reaktiv fosfor genom svepkoagulering. Eftersom storskaligt källsorterat avloppsvatten är en ganska ny företeelse, så finns det lite litteratur om fosforutfällning i gråvatten. Placering, dosering, kemikalier, och avlägsningsgränser för total fosfor har undersökts på gråvatten från RecoLab i Helsingborg, Sverige. Gråvatten taget efter den biologiska reningen krävde lägre dosering av koaguleringsmedlet och uppnådde lägre total restfosforkoncentration, kemisk syreförbrukning och grumlighet än det orenade inkommande gråvattnet. Beroende på reningsverkets utformning, kan fällning inom det biologiska steget (simultanfällning) ta bort eller minska risken av att fälla ut för mycket fosfor som kan minska effektiviteten i den biologiska reningen. Av de två kemikalierna som användes, hade det aluminiumbaserade koaguleringsmedlet (PAX-XL60, Kemira) bättre avskiljningseffektivitet än det järnbaserade koaguleringsmedlet (PIX-111, Kemira) vid de koncentrationer som används mest frekvent i traditionella avloppsreningsverk. Fosforavlägsnande under detektionsgränsen av 0,05 mg P/L uppnåddes med 15 mg Al^{3+} /L eller 45 mg Fe_{tot} /L i biologisk renat gråvatten medan för inkommande gråvatten uppnåddes lägsta koncentrationer på 0.16 mg P/L och 0.14 mg P/L total restfosfor genom att tillsätta 17 mg Al^{3+} /L respektive 36 mg Fe_{tot} /L.

Table of Contents

1 Introduction

As the understanding of the impact humans have on the environment grows, so do the restrictions intended to prevent irreversible damage to it. As a result, standards related to the release of nutrient compounds containing nitrogen and phosphorous are becoming more stringent throughout the world and especially in Sweden (Morling, 2019). In response, new and innovative ways to treat wastewater for extremely low nutrient levels have started to become more common place in society. One of these methods is the separation of domestic wastewater into different streams, based on where those wastewaters are generated within the building. The most common division of wastewater is into greywater and blackwater streams where blackwater is of toilet origin and greywater is all other domestic wastewater.

The division of water into streams allows for more specialized and targeted treatment towards specific pollutants at higher concentrations with lower volumes. There are many methods for treating greywater, but literature thus far has focused on onsite treatment with the intent for reuse (Boyjoo *et al.*, 2013; Ghunmi *et al.*, 2011). As source separation technology becomes more widely spread, the way municipal wastewater treatment works will shift. Oceanhamnen, a district in Helsingborg, Sweden already uses a source separation approach with a pilot treatment plant called RecoLab. At this plant, greywater, blackwater, and food waste streams are treated in separate processes. Right now, the plant uses enhanced biological phosphorous removal followed by settling, drum filter filtration, and nanofiltration to treat greywater with a final destination in Öresund. To enhance phosphorous removal, RecoLab is considering the addition of a chemical precipitation step within the plant.

Helsingborgs stad is also building a new district called Östra Ramlösa that will incorporate separated wastewater streams into the design. It was decided that greywater would be treated in a nearby treatment plant and released into a local stream. The treatment consists of moving bed bioreactors (MBBR), precipitation and sedimentation, disc filtration, and spray filtration followed by polishing using a submerged wetland. The receiving stream is small and therefore the levels of nutrients, particularly phosphorous, leaving the treatment plant need to be extremely low. Boyjoo *et al.* (2013) showed in a review of more than 30 papers on different types of greywater treatment that extremely low phosphorous levels are hard to achieve without the use of large constructed wetlands or precipitation. While a constructed wetland is part of the current treatment plan, precipitation will likely be needed to achieve the desired water quality regarding phosphorous.

Recent literature reviews have cited a total of 20 unique sources on chemical processes in greywater treatment with only 5 pertaining specifically to coagulation. Only three of those sources contained influent and effluent phosphorous measurements (Pidou *et al.*, 2008; Pidou *et al.*, 2007; Šostar-Turk *et al.*, 2005) cited via (Boyjoo *et al.*, 2013; Ghunmi *et al.*, 2011; Li *et al.*, 2009). This lack of information on the location and dosing of chemical precipitants in greywater treatment plants can make their design and operation challenging. Thus, more research is needed on the effectiveness of chemical precipitation of phosphorus in greywater, especially in regards to reaching very low concentrations.

1.1 Aim of Thesis

The aim of this project is to investigate chemical precipitation of phosphorous to meet more stringent effluent standards in biologically based source separated greywater treatment systems for direct release into the environment. To achieve this, the following questions will be answered.

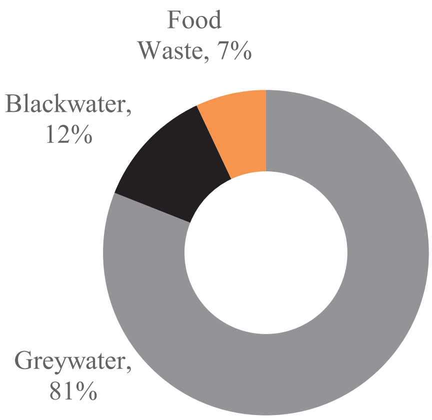
- What is the absolute lowest achievable phosphorus concentration?
- To what degree can phosphorous be removed at realistic dosing ranges?
- Where should precipitation be placed?
- What precipitant should be used?

2 Literature Review

Greywater is generally defined as all domestic wastewater that does not originate from the toilet, with toilet water being defined as blackwater. However, the exact definition of greywater is up for debate. This section explores the different definitions of greywater, how that effects water quality, and how greywater is treated.

2.1 Greywater Characteristics

Low strength greywaters tend to only include wastewater generated from wash basins and showers while high strength greywater can contain wastewater from laundry machines and/or kitchen sinks in addition to showers and wash basins. Regardless of what types of sources are included, greywater tends to be cleaner, accounting for up to 75% of the wastewater produced (Noutsopoulos *et al.*, 2018) while only containing around 30% of the total phosphorous concentration compared to mixed wastewaters (Ghunmi *et al.*, 2011). This “diluted” effect is reflected in other standard parameters like biological oxygen demand (BOD) and nitrogen but does not necessarily transfer to suspended solids (Boyjoo *et al.*, 2013). Greywater characteristics for the water used in this project can be seen in Figure 2.1.



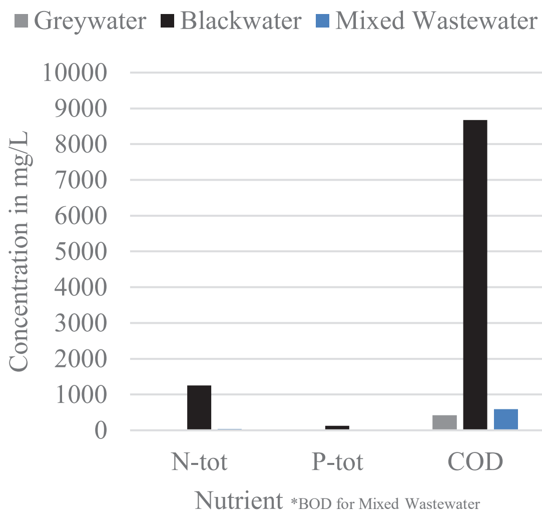


Figure 2.1 Wastewater flow percentages (left) and nutrient concentrations (right) in water entering RecoLab and Öresundsverket in Helsingborg, Sweden.

For the water in this study, a majority of what flowed into the plant was greywater, while blackwater held the majority of the nutrients. Compared to the mixed wastewater flowing, greywater was still less concentrated in regards to every nutrient.

Research has shown that the largest contribution of nutrients to greywater are kitchen sinks due to the nutrients introduced via food waste and laundry machines due to the existence of nitrogen and phosphorous as phosphates in detergents (Edwin *et al.*, 2014; Eriksson *et al.*, 2002; Jefferson *et al.*, 2004; Palmquist and Hanaeus, 2005). It is important to note that the presence and concentration of contaminants and pollutants in greywater is highly dependent on consumer activities and personal care products that consumers use in specific areas. For example, much of the research characterizing greywater in the Nordic region was done prior to the introduction of bans on phosphates in laundry detergents in 2007 and dishwasher detergents in 2010 (Miljödepartementet, 2014). Due to these bans, concentrations of phosphorous in greywater are expected to be lower than those reported in literature. Consumer habits between countries and differences between urban, suburban, and rural settings could also factor into the characteristics of greywater.

2.2 Greywater Treatment

Due to the relatively low levels of contaminants in greywater, it can be treated with less intensive and more cost-effective treatment mechanisms for reuse or release into the environment. A lack of standardization over reuse regulations throughout the world has led to different approaches ranging from nature based, low tech solutions up to expensive filtration schemes for the treatment of greywater. However, many existing small-scale greywater treatment systems focus more towards onsite reuse with eventual entry into sewage systems and employ biological and physical treatment schemes that tend to lack the required phosphorous removal rates on their own (Arinaitwe, 2018; Boyjoo *et al.*, 2013; Ghaitidak and Yadav, 2016; Ghunmi *et al.*, 2011; Li *et al.*, 2009; Pidou *et al.*, 2007). Constructed wetlands and reedbeds are shown to have more success in phosphorous removal due to their long retention times, use of specialized phosphorous sorption media, and plant uptake (Dallas *et al.*, 2004; Jenssen, 2005; Nolde, 2000). However, wetlands are not always a feasible option due to the large amount of space they require, which may not be available in semi-urban and urban areas, limiting their detention times and removal capacities.

These limitations have raised the question of whether phosphorous precipitation is a viable option to meet effluent standards for direct environmental release. There is a lack of literature pertaining to phosphorous precipitation in greywater specifically. In recent literature, only 20 unique sources have been cited about chemical processes in greywater treatment. Of those, only 5 pertaining specifically to coagulation. Three of those five sources included influent and effluent phosphorous measurements (Pidou *et al.*, 2008; Pidou *et al.*, 2007; Šostar-Turk *et al.*, 2005) cited via (Boyjoo *et al.*, 2013; Ghunmi *et al.*, 2011; Li *et al.*, 2009). Some research exists looking at advanced tertiary treatment for phosphorous removal in mixed wastewaters (Fundneider *et al.*, 2020; Scherrenberg *et al.*, 2011; Tooker *et al.*, 2010), coagulation for the removal of suspended solids and BOD in greywater (Ghaitidak and Yadav, 2016; Pidou *et al.*, 2008), and coagulation of commercial laundry greywater (Šostar-Turk *et al.*, 2005). What research does exist for greywater tends to focus on coagulation in conjunction with filtration (Friedler and Alfiya, 2010; Kasak *et al.*, 2011). This can make it hard to determine what portion of phosphorous removal comes from mechanical treatment and what comes from the coagulation-flocculation process alone. Furthermore, the specifics on the location and dosing of coagulants in conjunction with biological treatment in the context of greywater are yet to be researched extensively.

3 Study Locations

Two treatment schemes were considered during experimental design; the preexisting treatment scheme that services Oceanhamnen at RecoLab and the proposed treatment scheme to treat greywater from the new city district of Östra Ramlösa. Their characteristics and designs are discussed in this section.

3.1 Oceanhamnen and RecoLab

In 2020 the city of Helsingborg completed stage 1 on a new development along the harbor called H+. This whole neighborhood will eventually service 11000 residents in up to 5000 apartments and is expected to be completed in 2035 (Olsson *et al.*, 2013). Of those, about 2500 people will live within the city district Oceanhamnen. This project differs from traditional development through the use of separated wastewater streams. Oceanhamnen uses the "three pipes out" approach to separate wastewater into toilet origin (blackwater), kitchen origin (food waste), and all other domestic wastewater, including laundry machines (greywater). For each wastewater, a separate pipe transports them to the nearby wastewater treatment plant Öresundsverket, were the source separated wastewaters are treated at a test facility named "RecoLab". RecoLab is a pilot plant focused on resource recovery in the form of heat, energy, and nutrients. There are three separate treatment schemes for the different water types.

The scheme for greywater can be seen in Figure 3.1. The main greywater treatment process uses a combination of anaerobic and aerobic activated sludge reactors to achieve enhanced biological phosphorous removal. This is followed by sludge sedimentation, drum filtration, and nanofiltration prior to discharge of the effluent. At the start of this project, January 2022, the plant was treating about 50 m^3/d which constitutes approximately 25% of the design flow; but has the ability to expand as Oceanhamnen continues to be completed and more wastewater is being generated. New buildings were finished and inhabited throughout the spring and a small increase in flow was achieved around April, at the conclusion of the experimental phase, which is assumed to have had negligible impact on the experimental work. As of January 2022, there already existed about 1 year of weekly influent and sedimentation effluent total phosphorous and phosphate data from NSVA analysis lab and from an external verification laboratory. Table 3.1 shows the concentration of COD and nutrients (N and P) in water entering RecoLab and Öresundsverket as well as literature values of similar greywater (i.e. greywater containing laundry effluent). Greywater was more similar to mixed wastewater overall but was lower strength in all factors.

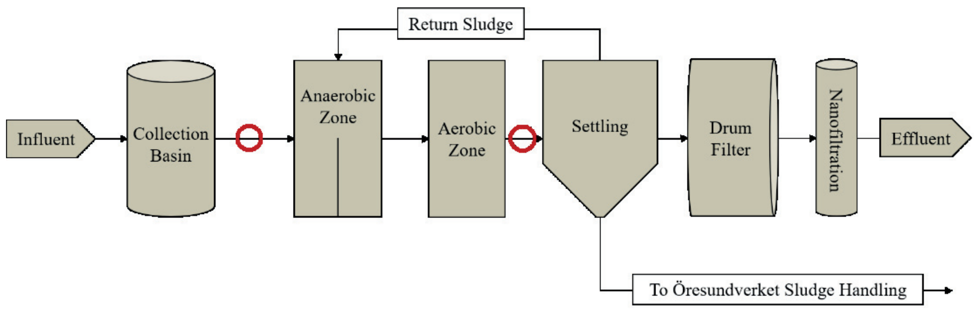


Figure 3.1 Treatment scheme for greywater at RecoLab pilot plant for Oceanhamnen during the spring of 2022. Sampling points circled in red.

Table 3.1 Wastewater Characteristics at Öresundsverket

Parameter	Öresundsverket Mixed Wastewater[1]	RecoLab Blackwater[2]	RecoLab Greywater[2]	Similar Greywater from Literature
Flow (% of total domestic wastewater)	100	12	81	65-96[4]
N-tot (mg/L)	41	1 250	17	8.8-57.7[4] 2.6-4.4[5]
P-tot (mg/L)	5	123	1.4	6.2-19.5[4] 0.37-5.43[5]
COD (mg/L)	595	8 680	420	245-1000[4] 398-861[5]
TSS (mg/L)	120-400[3]	3410	124	12-168[4] 77-166[5]

[1]Öresundsverket (2020) [2]Internal RecoLab data 2021 [3]Davis (2010) [4]Boyjoo *et al.* (2013) [5]Noutsopoulos *et al.* (2018)

Compared to the general wastewater arriving at the larger Öresundsverket, nitrogen and phosphorous concentrations are 2.5 and 3.6 times smaller while total COD is 1.4 times smaller than BOD alone at Öresundsverket. Looking at the characterizations of greywater by Eriksson *et al.* (2002), Jefferson *et al.* (2004), Boyjoo *et al.* (2013), Edwin *et al.* (2014), and Noutsopoulos *et al.* (2018), the average mixed wastewater which included laundry contains a BOD/COD ratio of about 0.5:1 meaning that COD might be closer to 2.8 time more dilute in greywater. Thus, greywater seems to be about three times as dilute compared to mixed wastewater in regards to these parameters.

Additionally, the measured flowrates indicate that 81% of the total domestic wastewater flow from Oceanhamnen to RecoLab is greywater while the remaining 19% is blackwater (12%) and food waste (7%). RecoLab operates as a treatment step within the larger Öresundsverket at the moment and therefore operates under the same environmental permit. At current, the permitted phosphorous concentration in the effluent is 0.5 mg P/L (Öresundsverket, 2020) but this will likely decrease to 0.2 or 0.3 mg P/L when renewing the environmental permit of the Öresundsverket wastewater treatment plant.

When comparing between the measured greywater from RecoLab and greywater reviewed in literature, two things become clear. As stated prior, greywater is extremely variable and dependent on consumer habits. For example, the amount of laundry detergent someone adds to a load of laundry will greatly affect the characteristics of greywater that exits the machine, or someone leaving the water on while washing their hands or brushing their teeth as opposed to turning it off and back on. Showering habits effect how concentrated constituents are within the greywater as well. Boyjoo *et al.* (2013), whose review includes studies on greywater in Sweden show that all parameters in RecoLab greywater are consistent with those in literature apart from phosphorous. This is likely due to the fact that the review was published in 2013 and a ban on phosphorous in detergents in Sweden went into effect in 2007 for laundry machines and 2010 for dish washing machines (Miljödepartementet, 2014), likely playing a factor in the lower concentration of phosphorous in RecoLab greywater since the studies being reviewed were published before the ban went into effect. Another study by Noutsopoulos *et al.* (2018) into characterizing greywater in Greece shows similar findings that RecoLab greywater is considered to be within expected ranges with the exception of nitrogen. Total nitrogen appears to be above the expected range. This could be due to human practices that diverge from other cultures, i.e. urinating in the shower, use of cloth diapers that are washed in household laundry, or soap and personal care product choices that may result in a high concentration nitrogen source being introduced into the greywater stream. A study published by Naturvårdverket (1995) showed that urine accounts for 80% of nitrogen in wastewater, so there is a likelihood that small additions of urine via showers or laundry could impact nitrogen concentration in greywater greatly, especially if water saving measures are used which could further diminish the effect of dilution. More information would be needed to better understand the cause of the deviation. However, for the scope of this thesis both the phosphorus and the COD concentrations can be assumed as representative for a normal greywater when compared to literature sources

3.2 Östra Ramlösa

Helsingborg is also building a new district called Östra Ramlösa in a more suburban setting. This new district will have 3000 housing units, serving up to 10000 people. Source separation based on the system in Oceanhamnen will be used with a decentralized, near-site greywater treatment plant. The proposed treatment scheme (Ridderstolpe *et al.*, 2021) is a combination of a two stage MBBR system and a 3500 m^2 submerged wetland filter as seen in Figure 3.2. Combined with the spray filters and dam, all of the steps after disc filtration will require 7000 m^2, or a space equal to one football pitch. The intention is to treat greywater to a degree where it can be directly released into a nearby stream, meeting very low discharge limits for phosphorus and thereby meeting the limits assumed from the national interpretation of the EU Water Directive. As previously stated, while wetlands can achieve the phosphorous removal required, they are large in size and it can be challenging to allocate adequate space in developed areas. Therefore, other treatment options may need to be used. Because of this, precipitation is being considered as an option to enhance phosphorous removal. The exact specifications of dosing and location are yet to be determined. The two locations under consideration are represented with the dotted lines in Figure 3.2.

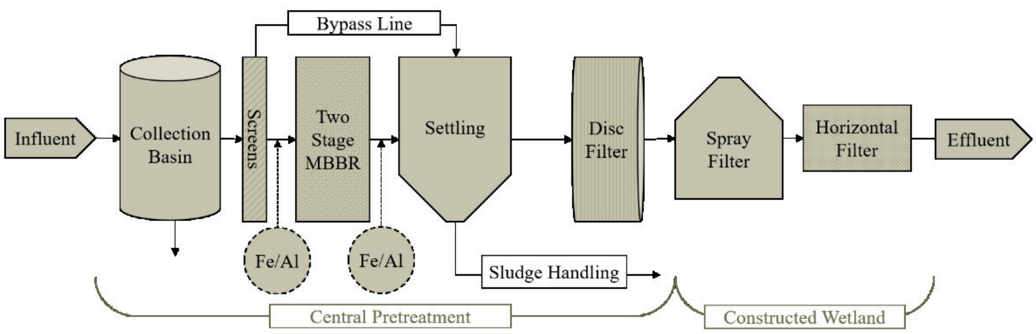


Figure 3.2 Treatment scheme at the proposed Östra Ramlösa plant. Proposed chemical precipitation points denoted with dotted lines (simplified, coagulation and flocculation tank placement decided upon final precipitation placement decision).

The main differences between the current RecoLab pilot plant and the proposed Östra Ramlösa treatment processes are that RecoLab relies on enhanced biological phosphorous removal (EBPR) in activated sludge basins while Östra Ramlösa will use MBBR for the biological step, the latter being more compact. The analogous positions at RecoLab to the proposed locations of chemical addition in Östra Ramlösa are directly after the collection tank for pre-precipitation and directly after the activated sludge stage and before sedimentation for simultaneous precipitation (red circles in figure 3.1). While biological phosphorous removal will happen to a degree in Östra Ramlösa, it will not be encouraged, monitored, or controlled in the same way and therefore is not likely to be nearly as efficient as in RecoLab. Kängsepp *et al.* (2020) showed that in mixed wastewater, an MBBR process was capable of removing around 35% of the total phosphorus without the use of EBPR while a study on greywater including laundry effluent for a building in Brazil achieved only 12% removal of total phosphorous via MBBR and settling (Chrispim and Nolasco, 2016). In comparison, historical data from RecoLab pilot plant (prior to sludge washout in February 2022) shows removal rates around 72% for total phosphorous and 74% for phosphates by the effluent point of sedimentation without the use of chemical precipitation. Therefore, phosphorous levels after biological treatment from Oceanhamnen and the actual water at the same stage from Östra Ramlösa may differ. However, due to sludge washout in RecoLab at the beginning of the project, the efficiency of EBPR is less likely to create a major difference between the biological phosphorous removal rates at RecoLab and those expected in Östra Ramlösa.

4 Phosphorous Removal

Phosphorous enters wastewater through human waste, food waste, personal care products, and cleaning products. If wastewater is released without proper treatment, this phosphorous can be consumed by organisms in the environment, causing eutrophication. In this process, algae can grow and create both aesthetic and water quality issues. Dead zones created when overgrowth uses up dissolved oxygen can cause mass die offs that create less than desirable smells and make streams uninhabitable for fish. Algal blooms can take over water bodies and turn water green and murky. In some cases, algae can produce harmful toxins, making natural water bodies hazards to human health. Because of these risks, the form and concentration of phosphorous present and how to remove it are important aspects of wastewater treatment.

Phosphorous is primarily present in wastewater in the forms of organic phosphorous and phosphates. Between 18 to 32% of the soluble phosphorous in mixed wastewater can be classified as nonreactive (sNRP) in the form of organic phosphorus and inorganic condensed acids (Tooker *et al.*, 2010) while reactive phosphorus takes the form of ortho or polyphosphates. Since much of the phosphorous in greywater is from detergents in the form of polyphosphates as opposed to organically bound phosphorous, this percentage is expected to be lower in greywater but has not been quantified. There are three main forms of phosphorous removal in wastewater treatment: biological, physical, and chemical. Because of the nature of sNRP, it can be seen somewhat as the limit of removal for biological and chemical treatment. In contrast, phosphate is the easiest to remove because it readily reacts with chemicals and is easy for cells to assimilate.

4.1 Biological and Physical Treatment

While phosphate can be removed via biological treatment mechanisms, phosphate uptake and assimilation into cells occurs in a ratio of BOD:P=100:1 in aerobic activated sludge systems, meaning one mg P/L of phosphorus is removed from the water for every 100 mg O_2/L of BOD (Metcalf and Eddy, 1991). Since up to 30% of the total phosphorous could be nonreactive and only 1 mole of phosphorous is removed per 100 moles of BOD, biological treatment often cannot remove phosphorous to the degree necessary, historically in excess of 90% (Morling, 2019). Additionally, if coupling biological treatment with any form of precipitation, the placement of the precipitation needs to be considered so as to not cause phosphorous limitation in the biological step, which has been observed in previous studies (Jefferson *et al.*, 2001; Scherrenberg *et al.*, 2011). Phosphorous can also be removed via filtration but Friedler and Alfiya (2010) showed that the addition of a coagulation-sedimentation step greatly increases the removal efficiency of most parameters, even at the membrane scale, and reduces the rate of filter fouling. Physical treatment is also the main form of treatment to remove sNRP, which becomes an important consideration at extremely low concentrations.

4.2 Chemical Treatment

Chemical wastewater treatment most often takes the form of precipitation. There are four potential ways precipitation can be used. The first of those is defined as pre-precipitation. This is when coagulants are added prior to the biological step and requires a primary settling location. As mentioned above, this can cause issues related to phosphorous limitation later on in the biological stages if too much phosphorous is removed. It also creates a second sludge stream and typically requires more chemicals to meet the required effluent standard than other types of precipitation, such as post-precipitation.

The second style is direct precipitation which is the same as pre-precipitation without being followed by a biological step. Since a biological step is present in both the treatment schemes considered, this is outside the scope of this study and will not be considered.

The third style is simultaneous or co-precipitation. This process does not use a separate basin, but instead adds the coagulant directly to the biological step. Even if the addition happens after the biological treatment stage, flocs and excess coagulant are transported back to the biological step in return sludge from the settling stage. Therefore, it is still considered simultaneous precipitation. This increases the amount of sludge produced in this stage and can create some issues for certification for use of sludge as a fertilizer on agricultural land (i.e. REVAQ, Finnson (2022)) since the biological and chemical sludges are mixed. Despite this, it is often used to target phosphorous removal in traditional mixed wastewater treatment plants. Due to a very high concentration of suspended solids in many biological processes, there tends to be a higher ratio of coagulant to phosphorous, since there are more substances competing with phosphates to interact with them. EBPR is used at RecoLab compared to MBBR in Östra Ramlösa, so the sludge in the biological stage may have different properties and therefore require different dosing if the phosphorous to suspended solids ratio differs significantly.

The final style is post-precipitation, where coagulants are added after the biological step. This can be expensive because extra basins are needed and an additional sludge is created, but this process produces a separate chemical sludge which makes sludge reuse certification easier. This type of precipitation can greatly enhance phosphorous removal efficiency. The DOC reduction due to precipitation (Du *et al.*, 2018) can also reduce dosing required in advanced treatments that target the removal of organic micropollutants, like ozonation. Because of the RecoLab and Östra Ramlösa designs, which does not include a design for tertiary settling, this process will not be considered in the context of RecoLab during this study but post-precipitation without settling is considered for Östra Ramlösa.

4.3 Precipitation Theory

Phosphorous precipitation is mediated by the use of coagulation and flocculation. Precipitation is considered the action of using chemicals to react with dissolved substances to form solids that can be separated out of solution. Coagulation is defined as the process of adding chemicals to water to neutralize charges, allowing small particles to attract. Flocculation is defined as the stage where the now neutralized suspended particles aggregate to form flocs that can be more easily separated or settled out of the water column. As these particle groups fall, they pick up other particles along the way that become intertwined in the mass in a process called sweep coagulation. This sweep coagulation is important when considering extremely low concentrations because it has the ability to remove nonreactive phosphorous.

During the process of coagulation, the metal salts hydrolyze and act differently in the presence of an acid or alkaline solution. The two main forms of metal salt coagulants used today are aluminum-based and iron-based. However, due to the interactions of these chemicals with water and the naturally occurring buffer carbonate, these salts have varying efficiencies at different pH conditions. In inadequate alkalinity, both aluminum and iron-based salts can decrease pH, further affecting their efficiency. However, treatment plants handle large volumes of water so it is not often that pH adjustment is used. Therefore, the choice of coagulant often depends on the unaltered pH of the incoming water and the optimum operating pH for the specific coagulants considered. This project will consider both PIX-111 (Kemira, 13.8% Fe_{tot}, <0.3% Fe^{2+}, Density: 1.42 g/m^3) and PAX-XL60 (Kemira, 7.5% Al^{3+}, 14.2% Al_2O_3, density: 1.31 g/m^3). These two coagulants were chosen due to their frequent use in municipal wastewater and previously proven abilities to achieve low phosphorous concentrations (Väänänen, 2014; Väänänen, 2017).

Once particles are conditioned with the coagulant, flocculation starts to occur at the micro scale through natural diffusion but mixing allows for more interaction and creates larger flocs. As the flocs grow, they begin to settle at different rates based on size, creating more collisions and even larger flocs. The mixing time needs to be considered so that the net formation and breaking up of flocs due to the shear forces within the water are at equilibrium. The decision on mixing speeds and times are considered in the next section of this report.

Flocculation and coagulation do tend to be good at removing phosphorous but are often only considered in the context of removing suspended particles. While there is not a large amount of information available about the exact breakdown of phosphorous in greywater, a substantial portion of total phosphorous, up to 40%, is in the form of phosphates (Noutsopoulos *et al.*, 2018). Furthermore, Tooker *et al.* (2010) observed that the total phosphates and soluble phosphates were not significantly different in mixed wastewater, indicating that the phosphates that are present in wastewater are readily reactive. These coagulants react with soluble phosphates to form a precipitate as seen in equations 3.1, 3.2, 3.3 and 3.4.

$$Al^{3+} + PO_4^{3-} \leftrightharpoons AlPO_{4_{(s)}} \quad \text{(Eq. 3.1)}$$

$$3Al_2O_3 + 6PO_4^{3-} + 18H^+ \leftrightharpoons 2Al_3(PO_4)_{3_{(s)}} + 9H_2O \quad \text{(Eq. 3.2)}$$

$$Fe^{3+} + PO_4^{3-} \leftrightharpoons FePO_{4_{(s)}} \quad \text{(Eq. 3.3)}$$

$$3Fe^{2+} + 2PO_4^{3-} \leftrightharpoons Fe_3(PO_4)_{2_{(s)}} \quad \text{(Eq. 3.4)}$$

The Kemira Water Handbook (Shestakova *et al.*, 2020) states that 1.8 to 2.7 g of Fe^{3+} are needed to remove 1 g of orthophosphate and 0.87 g of aluminum is required to remove 1 g of orthophosphate, assuming a molar ratio of 1. Using the values from Table 3.1, that means that mixed wastewater from the Helsingborg (which had 5 mg P/L) would need a dosing range of 9 to 14 mg Fe^{3+} /L or between 4 and 7 mg Al^{3+} /L at a minimum if all phosphorous is in the form of phosphate, although the handbook notes that many factors may increase the amount required, especially if extremely low (<0.2 mg PO_4^{3-}-P/L in effluent) phosphorous concentrations are sought after.

While there are theoretical calculations for the exact amounts of chemicals to be added and the mixing time for the formation of flocs, these reactions tend to be extremely complicated. The wide variety of contaminants and varying concentrations, known as the cocktail effect, make it even harder to calculate the required dosing and mixing time without the help of experimentation as indicated by Fundneider *et al.* (2020), who showed that an over-stoichiometric addition of coagulants is required to achieve extremely-low phosphorous concentrations and that the concentrations required vary heavily based on water parameters. As a result, dosing and mixing parameters are determined via jar tests which will be discussed in more detail during the methods section of the report.

5 Materials and Methods

The investigation into phosphorous precipitation was completed at the laboratory scale using jar tests with varying doses of precipitants. Water was collected from the greywater treatment scheme at RecoLab which has already been operating for 1 year. Phosphorous concentrations were quantified initially through ion chromatography and later through Hach Lange Cuvettes. Additionally, visual observation was used during the proof of concept phase to ensure dosing was realistic. The rate of floc formation, floc size, settling speed, and resulting water clarity were considered in visual analysis. Turbidity and COD were also measured after the first phase of experimentation in an attempt to make a connection between total phosphorous concentration and those two parameters. Total nitrogen was also measured to see the possible effect that precipitation could have on nutrient ratios and the subsequent biological treatment of the wastewater.

5.1 Sample Collection

Grab samples were collected from RecoLab on the dates seen in Figure 5.1. Influent greywater grab samples were taken at the collection tank of raw greywater to simulate pre-precipitation. Grab samples were also taken at the effluent point of the aerobic tank to simulate simultaneous precipitation and were denoted as biologically treated greywater. These locations are considered to be analogous to the alternative points of chemical addition in the planned treatment scheme in Östra Ramlösa.

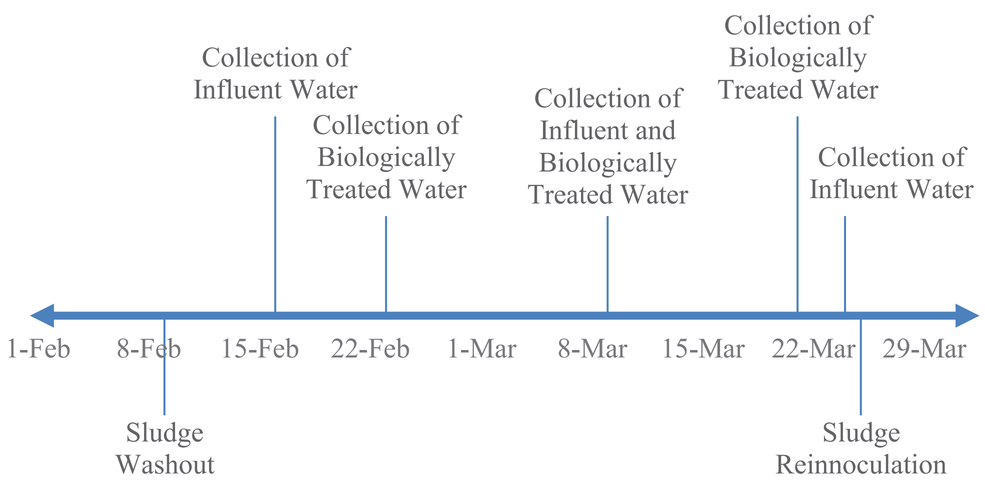


Figure 5.1 Sample Collection Timeline in relation to sludge events.

After collection, samples were transported and stored at 4°C for no more than 48 hours before jar testing, because untreated greywater can change rapidly at ambient temperatures due to the presence of microorganisms (Dixon *et al.*, 2000).

5.2 Jar Tests

Coagulant optimization was carried out for both PIX-111 and PAX-XL60 using the Flocculator 2000 from Kemira. Of the collected water, 1 L from each sampling point was allocated for each of the coagulants at the chosen molar ratios. Each sampling event included one treated control that underwent jar tests for each sampling point. Some water was reserved and tested immediately to determine the volume of coagulant required based on the initial concentration of total phosphorous present.

5.2.1 Phosphorous Concentration Determination

Historical data from RecoLab was used to determine the amount of phosphorous present in influent greywater so that the volume of coagulant to be added could be determined during the proof of concept phase, which relied on qualitative measures. A recent average (November 2021-February 2022) of internal data was used since the plant had an increase in the number of people serviced throughout the course of operation. Therefore, the recent average is seen as more representative of current plant operation, rather than an overall average. This was found to be 1.47 mg P/L (see Figure 5.1), similar to an external verification laboratory of about 1.30 mg P/L. Similarly, a recent average of influent phosphate concentration was found to be 0.60 mg PO_4^{3-}-P/L. The external laboratory did not measure phosphates so no comparison can be made.

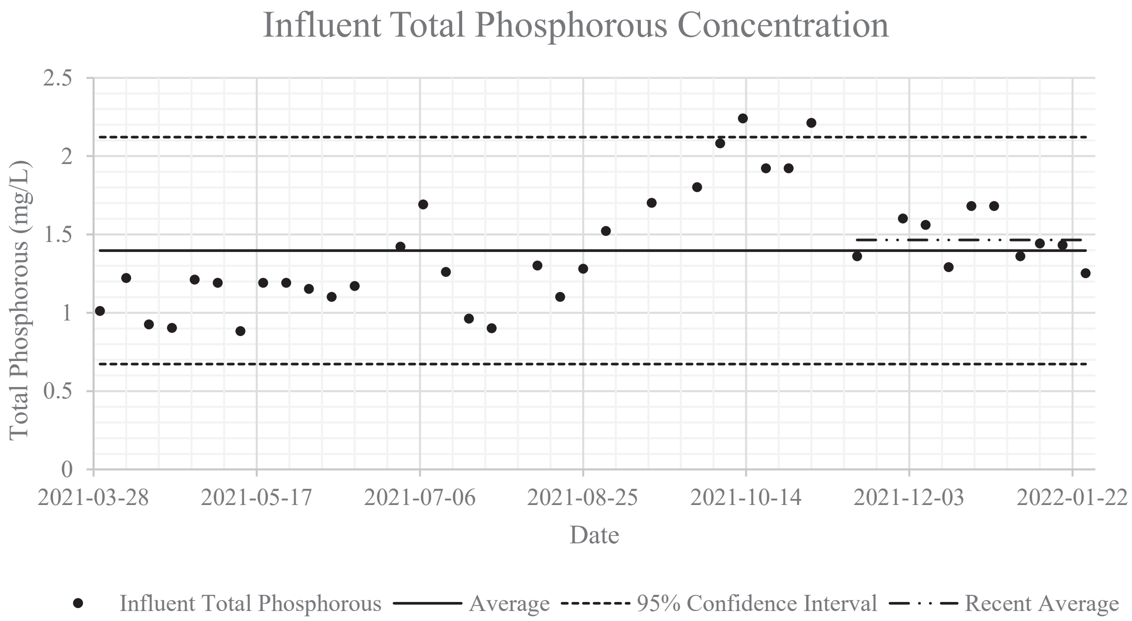


Figure 5.1 Historical Total Phosphorous Concentrations in influent greywater to RecoLab.

Currently, the concentration of total phosphorous or phosphates is not measured internally at RecoLab between the influent point and after settling. Therefore, the concentration and removal of phosphorous due to biological treatment is unknown. However, it is traditionally accepted that activated sludge processes remove between 20-30% of phosphorous. Considering RecoLab contains no primary settling stage and about 25% of phosphorous in influent water is phosphate as well as the potential increase is phosphorus removal from EBPR as it was operating during experimentation, an estimate of 70% of incoming total phosphorus makes it through the biological stage. Since the main form of biologically available phosphorous is orthophosphate, it is assumed that the decrease in total phosphorous is due to the removal of phosphates. Based on average concentrations, this means that there is about 1.0 mg P/L total phosphorous and 0.16

mg PO_4^{3-}-P/L phosphate remaining after the biological treatment step. A sample of biologically treated greywater was tested for phosphate and was found to be below a detection limit of 0.1 mg P/L, supporting this assumption. The theoretical total phosphorous concentration was used for dosing biologically treated greywater during the proof of concept phase.

It was decided that the total phosphorous concentration would be used for dosing during the duration of the project. After the proof of concept phase, the total phosphorous concentration was measured for both influent and biologically treated greywater and coagulants were dosed based on the concentrations present in the water sample, not the long-term average.

5.2.2 Molar Ratio Determination

Based on the relationship between ferric chloride and phosphate shown in Eq 3.3, the minimum theoretical ratio of iron to phosphorous is 1:1 so the coagulant does not act as the limiting factor, Fundneider *et al.* (2020) showed that in mixed wastewater molar ratios between 2 and 20 mole iron per mole soluble reactive phosphorous (sRP) removed were required to achieve effluent sRP concentrations between 50 µg/L and 5 µg/L, respectively. This study looked at coagulation and flocculation in conjunction with cloth filtration, so the proportion of removal due to precipitation cannot be stated exactly, but it can be used as a general guide since cloth filtration acts only as a separation technology and not a biological or chemical removal mechanism. In the subsequent report, molar ratios are discussed as their number, with a unit of moles coagulant per moles total phosphorous initially in the corresponding water sample. These are referred to as the molar ratio. Molar ratios of 5, 10, 20, 30, and 40 were used for the proof of concept to determine if this range was realistic. Similarly, Eq. 3.1 shows that the minimum theoretical ratio of aluminum to phosphorous is 1:1 so that the coagulant does not act as a limiting factor. Additionally, sRP effluent concentrations between 8 µg/L and 50 µg/L were achieved with molar ratios between 2 and 8 mol aluminum per mol sRP removed (Fundneider *et al.*, 2020). This study shows that there is a lower molar ratio needed to achieve comparable removal rates using aluminum-based coagulants. Therefore, to achieve similar molar ratio rates for aluminum, molar ratios of 2.5, 5, 10, 15, and 20 were used during the proof of concept. A summary of the molar ratios used during the proof of concept phase can be seen in Table 5.1

Table 5.1 Molar dosing ratio during Proof of Concept

PIX-111	PAX-XL60
2.5	5
5	10
10	20
15	30
20	40

During the proof of concept phase the jars with varying doses were observed visually (see Figure 5.3 for influent greywater and 5.4 for biologically treated greywater) and extracted for analysis with ion chromatography to understand in what range removal occurs. After the first set of tests, the ratios were adjusted and more points were investigated in areas where large changes occurred or where there appeared to be a minimum achievable concentration to better understand the behavior of coagulants in greywater. The proof of concept phase on influent greywater showed that both PIX-111 and PAX-XL60 were most effective in the theoretical molar ratio range of 5 to 15.

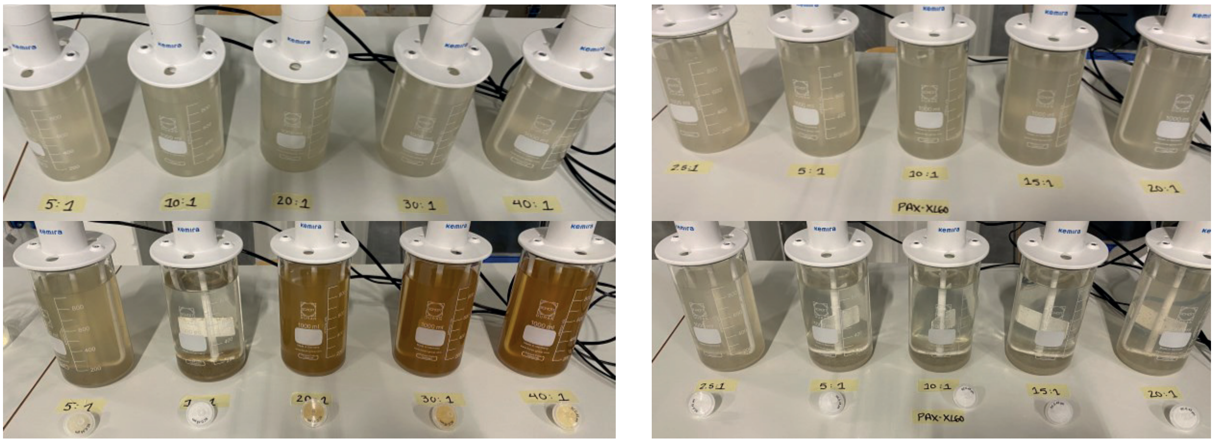


Figure 5.3 Jar tests on influent greywater using PIX-111(left) and PAX-XL60 (right) during the proof of concept stage.

The proof of concept phase on biologically treated greywater showed that both PIX-111 and PAX-XL60 were more effective as the molar ratio increased. For PIX-111, the coloration due to overdosing made it possible to see an upper limit of 30 but the same could not be observed in jar tests using PAX-XL60.

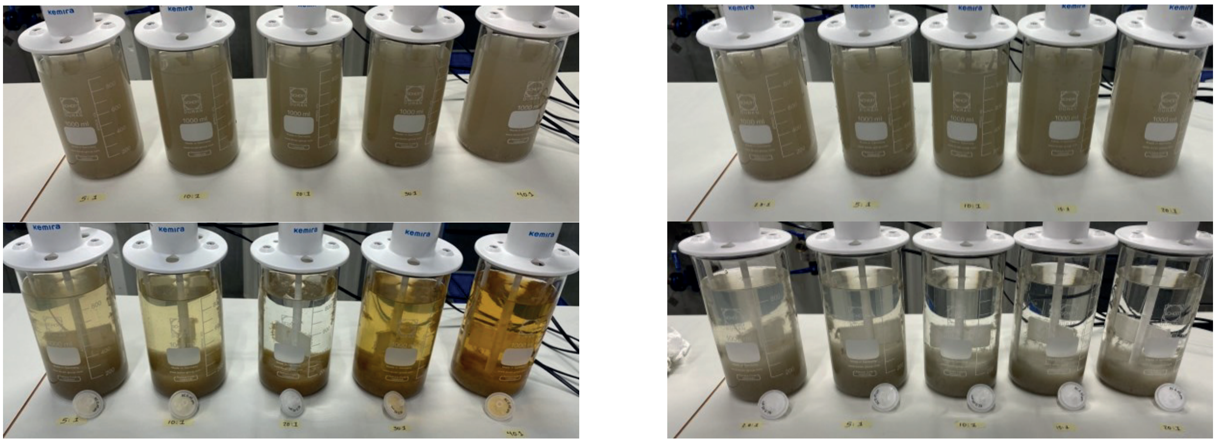


Figure 5.4 Jar tests on biologically treated water using PIX-111(left) and PAX-XL60 (right) during the proof of concept stage.

In all sampling events after the proof of concept stage, a sample of the water was tested for the total phosphorous concentration prior to dosing so that the molar ratios and their subsequent volume additions could be recalculated to better reflect the intended molar ratios.

5.2.3 Mixing Settings

Prior to jar testing, bottles were allowed to warm to ambient temperatures and shaken to disperse any settled solids during transport and storage. The unsettled samples were divided into 1 L jars.

Table 5.2 shows the suggested settings for mixed wastewater and surface water when using the Flocculator 2000. The Kemira handbook (Shestakova *et al.*, 2020) suggests that colder water will take longer to coagulate while higher turbidity requires a shorter time. Additionally, iron coagulated flocs can withstand longer slow mixing times and higher propeller speeds than aluminum coagulated flocs. Since the overall water characteristics are not that different than mixed wastewater from the same city, and the total suspended solids concentration lies within the accepted ranges, the suggested wastewater settings for mixing time and speed were used. Since the focus was on the ability to precipitate rather than the separation technology, a long settling time was chosen.

Table 5.2 Kemira suggested jar test settings (Shestakova et al., 2020)

Stage	Mixed Wastewater		Surface Water	
	Speed (rpm)	Time	Speed (rpm)	Time
Rapid Mixing	300-400	10 sec	300-400	20-30 sec
Slow Mixing	35-40	5-15 min	35-40	10-30 min
Sedimentation	-	10 min	-	15-30 min

Coagulants were added to the jars in the determined ratios and mixed rapidly at a rate of 300 rpm for a total period of 20 seconds. The first 10 seconds acted to disperse any settled solids during experiment set up. The coagulant was added after 10 seconds and mixed in for an additional 10. During slow mixing, water was mixed at a speed of 35 rpm for a period of 10 minutes. After mixing, the water was allowed to settle for 30 minutes. Samples of 20 mL were taken using a syringe at 3 cm below the water surface or high enough above the settled sludge to not disturb it if there was not 3 cm of clear water above the sludge. At each sampling event, a control jar with no coagulant addition was used for both influent and biologically treated greywater to determine the removal due to settling alone.

5.3 Quantification

In the initial phase of the project, visual analysis was used to better adjust the molar ratios prior to phosphorous analysis. Ion chromatography (IC) was also used to quantify phosphate concentrations at a detection limit of 0.1 mg P/L. Once jar tests were complete, water was filtered through a 0.45 μm filter before analysis. Samples were stored at 4°C until being analyzed via ion chromatography for their phosphate concentration. Blanks and standards were run to ensure that samples were not contaminated and accurately quantified. Ion chromatography was run with 1 injection per sample at a volume of 10 μL and no dilution. An established method for the analysis of nitrogen and phosphorus containing ions by the LTH Department of Chemical Engineering and their respective retention times was used for analysis. Initial runs found that phosphate concentrations in all samples but the untreated influent control and the molar ratio of 2.5 of PAX-XL60 in influent greywater were below detection limits. It is also possible that undetectable levels of phosphate exist during the biological treatment step but detectable levels can be seen in the effluent water (i.e. 0.1 mg P/L on the same day that greywater was collected and analyzed using ion chromatography) due to the presence of polyphosphate accumulating organisms (PAOs) in EBPR sludge (like that from RecoLab) that take up excess phosphate during aerobic periods but release phosphate during anaerobic periods that might occur during settling.

Therefore, Hach Lange low range phosphorous cuvettes (LCK 349; 0.05-1.50 mg P/L) were used to determine total phosphorous concentration after the first phase of sampling. Phosphorous cuvettes underwent hydrolysis at 100°C for 1 hour and cooled at ambient conditions before quantification. Samples were not filtered or centrifuged prior to total phosphorous quantification but care was taken to prevent the uptake of large floc or sludge into samples. Additionally, Hach Lange cuvettes were used to measure COD (LCK 314 15-150 mg O_2/L, LCK 514 100-

2000 mg O_2/L, LCK 714: 100-600 mg O_2/L) and total nitrogen (LCK 138 LATON: 1-16 mg N/L). Digestion for COD quantification was completed by heating the cuvettes to 148°C for 2 hours, cooling at ambient conditions, and allowing to settle completely before being analyzed. Total nitrogen digestion was completed by heating vials for 30 minutes at 120°C before cooling to room temperature and transferring to the cuvettes. Turbidity was also observed using a Hach Portable Turbidimeter Model 2100P directly after jar testing.

5.3.1 Quality Control

A small study was completed to ensure that Hach Lange cuvettes were accurate and that methods were being followed correctly. Three standards were made from a 1000 mg PO_4^{3-} /L Ion Chromatography standard at concentrations of 1.0 mg P/L, 0.5 mg P/L, and 0.1 mg P/L via serial dilution. The results of their analysis can be seen in Figure 5.5. These are all within the bounds of the phosphorous cuvettes used and lie either at or above the detection limit of the ion chromatography system used. After creation, standards were processed and analyzed for total phosphorous and phosphate with the Hach Lange cuvettes and run on Ion Chromatography. Standards measured accurate to the expected value when analyzed with Hach Lange cuvettes. Ion Chromatography tended to slightly overestimate the standards but was within expected deviation, although the lowest standard failed to be detected. Because the results of the influent and biologically treated greywater from the proof of concept showed low levels of phosphate, the decision to focus on total phosphorous was made so that detectable levels could be found.

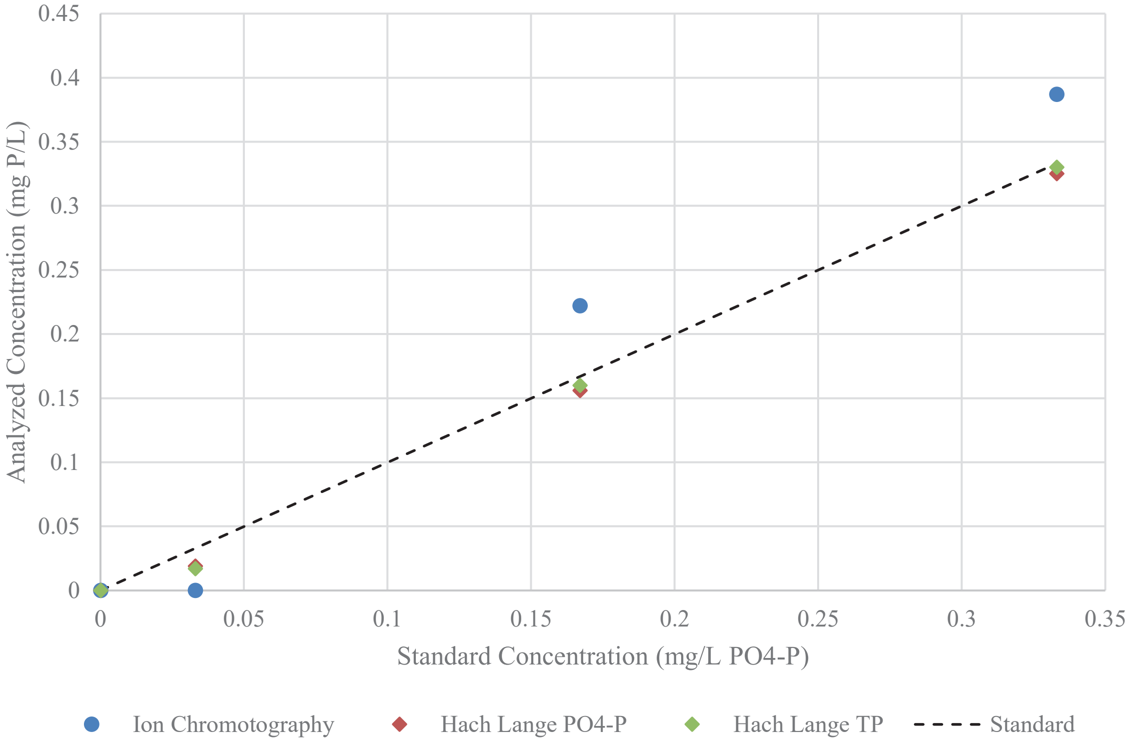


Figure 5.5 Comparison of analytical methods for phosphorous detection.

6 Results and Discussions

An initial proof of concept phase was completed for both influent and biologically treated greywater to ensure that the molar ratios chosen for the study were within reason. Based on the results of this proof of concept, a second round of sampling was completed within the most effective ranges from a visual analysis. This was followed by a final sampling event that focused on the lower molar ratio range but included high molar ratio points to test the limit of efficacy.

6.1 Chemical Precipitation in Influent Greywater

Prior to jar testing, the total phosphorous and COD concentrations were quantified and the measured total phosphorous concentration was used to determine the volume of coagulant added for each molar ratio. Samples were not filtered or centrifuged and turbidity was also measured at the end of each jar test. Controls for both influent and biologically treated greywater were used to see the enhancement effect that coagulation has in addition to settling.

After jar testing PIX-111, it was clear that molar ratio doses of 20 and above were overdosed. The water took on a rust color that did not disappear during the settling period. The flocs that formed were finer than that of the lower doses and the coloration made it hard to determine to what degree they settled. Additionally, molar ratios of 5 and below did not seem to have a great effect on the visual clarity of the water. The jar tests at slow mixing and after 30 minutes of settling can be seen in Figure 6.1.

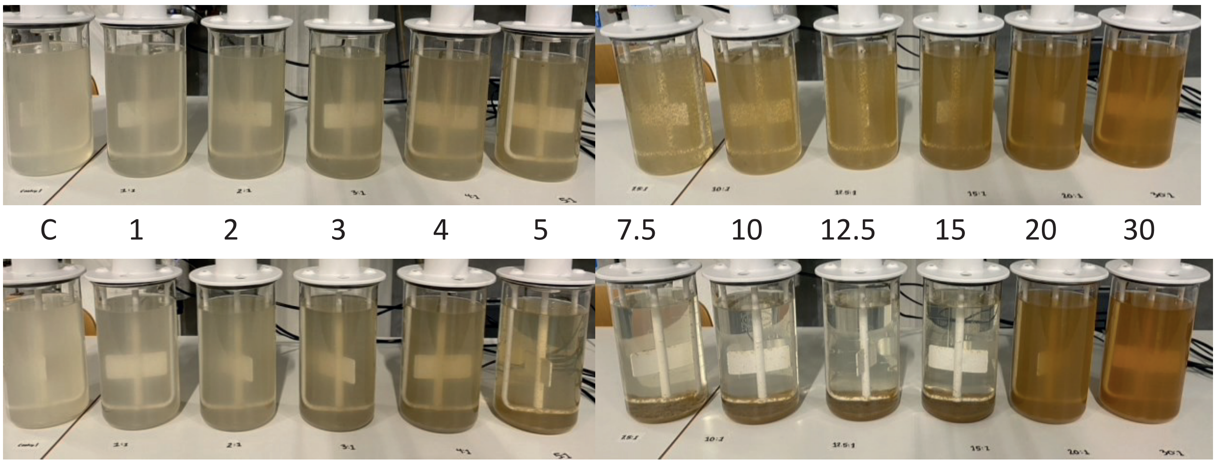


Figure 6.1 Jar Test for influent greywater using PIX-111 during slow mixing (upper) and after settling for 30 minutes (lower). Molar ratios listed in between the two timepoints.

The efficacy of PAX-XL60 was also tested using the same molar ratios since a visual proof of concept showed that molar ratio requirements for the two coagulants was similar, contrary to what was expected from previous literature (Fundneider *et al.*, 2020). It was easier to determine the sizes of floc as they formed during mixing when dosing PAX-XL60 because it did not color the water to the same degree as PIX-111. However, the lack of coloration in the water did make it harder to determine the maximum limit of efficacy. All the doses had some effect on improving water clarity but the molar ratio points from 4 to 15 did substantially better than the others. Jar tests during slow mixing and after 30 minutes of settling can be seen in Figure 6.2.

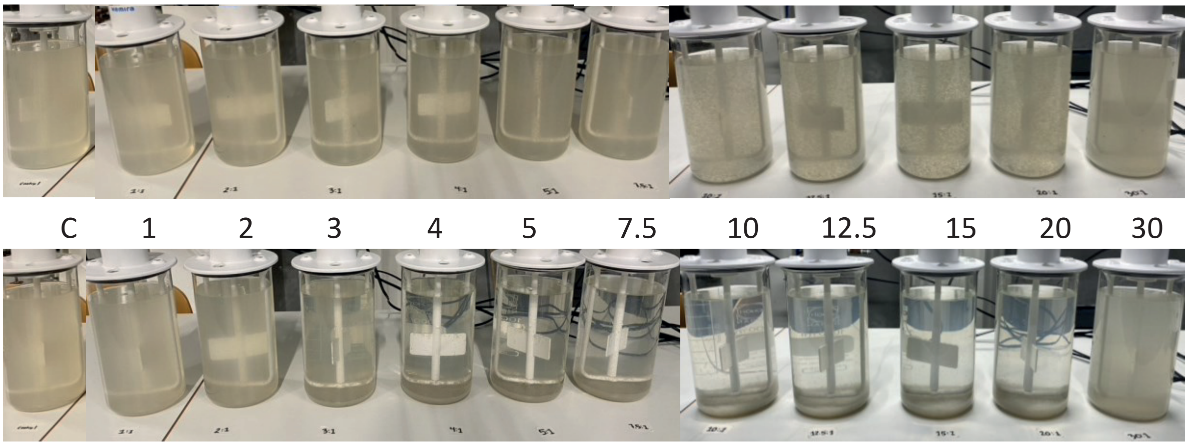


Figure 6.2 Jar Test for influent greywater using PAX-XL60 during slow mixing (upper) and after settling for 30 minutes (lower). Molar ratios listed in between the two timepoints.

Table 6.1 shows the characteristics of influent greywater from both sampling events. Water collected on March 9th, the total phosphorous concentration was found to be 1.57 mg P/L, slightly out of range of the cuvettes but still used to determine the dosing volumes. Untreated influent water had a turbidity of 217 NTU. For the sampling event on March 24th, influent COD was found to be 515 mg O_2/L with total phosphorous measuring at 1.48 mg P/L. The treated control had a COD concentration of 410 mg O_2/L, meaning that settling alone accounted for 20% of the COD removal. Similarly, the treated control had a total phosphorous concentration of 1.31 mg P/L, an 11% removal from settling alone. Turbidity differed slightly from the March 9th event at 179 NTU. On both days the settled sample had a turbidity close to 140 NTU, accounting for a turbidity removal of 25% on the 24th and almost 40% on the 9th. The measured total phosphorous was used to determine the amount of coagulant added for each molar ratio. Table 6.2 shows the molar ratios converted into mg/L as metal coagulant added (mg Me/L).

Table 6.1 Characteristics of influent greywater before experimentation (untreated) and after laboratory settling (treated control).

Parameter	2022-03-09	2022-03-24
Untreated		
TP (mg P/L)	1.57	1.48
COD (mg O_2/L)	-	179
Turbidity (NTU)	217	515
Treated Control		
TP (mg P/L)	1.35	1.31
COD (mg O_2/L)	-	410
Turbidity (NTU)	143	135

Table 6.2 Molar ratios as mg Me/L added to influent greywater.

	2022-03-09		2022-03-24	
Molar ratio	**PIX-111 mg Fe_{tot} /L**	**PAX-XL60 mg Al^{3+}/L**	**PIX-111 mg Fe_{tot} /L**	**PAX-XL60 mg Al^{3+}/L**
0	0	0	0	0
1	-	-	2.7	1.3
2	-	-	5.4	2.6
3	-	-	8.1	3.9
4	-	-	11	5.2
5	14	6.8	13	7
7.5	21	10	20	9.7
10	29	14	27	13
12.5	36	17	34	16
15	43	21	40	19
20	-	-	54	26
30	-	-	81	39

Figure 6.3 shows the effect that coagulant dosing has on residual phosphorous concentrations. PAX-XL60 tends to remove more phosphorous at lower doses than PIX-111 but it appears that after a certain dose, coagulation stops being effective and begins to approach the original concentration again. This occurs earlier for PAX-XL60 than PIX-111 and seems to be less abrupt. Due to the nature of coagulation, this inefficacy at high coagulant concentrations is likely due to the overflooding of positive ions in the water, inhibiting charge suppression, floc formation, and settling.

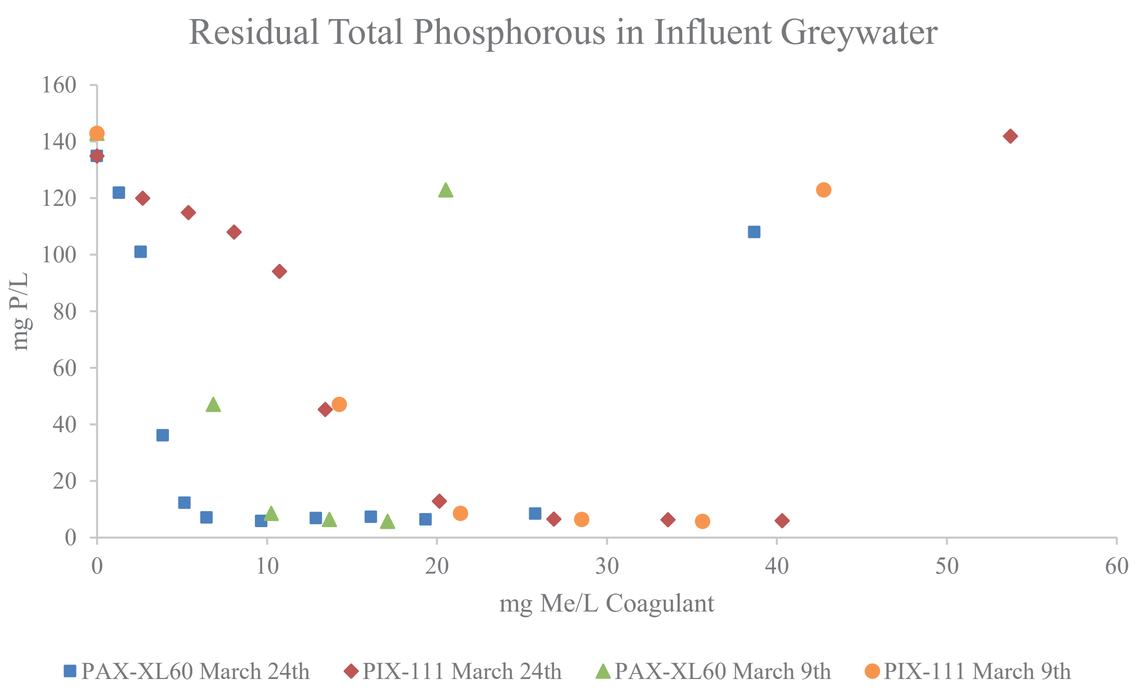


Figure 6.3 Residual Total Phosphorous after Coagulation in Influent Greywater

PIX-111 seemed to achieve lower residual total phosphorous concentrations than PAX-XL60. On March 9th, PAX-XL60 achieved a minimum concentration of 0.170 mg P/L total phosphorous while PIX-111 achieved a minimum of 0.143 mg P/L. On March 24th, PIX-111 achieved a concentration of 0.196 mg P/L total phosphorous while PAX-XL60 only achieved 0.277 mg P/L. With molar ratios between 5 and 15 corresponding to between 15-40 mg Fe_{tot}/L PIX-111 and 7-20 mg Al^{3+}/L PAX-XL60, removal rates were above 75%, maxing out at 81% for PAX-XL60 and 87% for PIX-111 on the 24th and 90% for PAX-XL60 and 91% for PIX-111 on the 9th. These high removal rates can be achieved with as little as 7 mg Al^{3+}/L PAX-XL60 and 15 mg Fe_{tot}/L PIX-111.

This increase in removal is an improvement of almost 80% over settling without coagulation but is similar to total phosphorous removal rate of more than 95% expectation by Väänänen *et al.* (2016) when both coagulants and polymers are used to enhance removal with recommended doses of 5-20 mg Al^{3+}/L or 10-30 mg Fe^{3+}/L in primary precipitation of mixed wastewater, with expected effluent concentrations of less than 0.3 mg TP/L. It is important to note that low influent concentrations in greywater influence removal percentages since the same differences in concentration account for larger portions of the influent in greywater than mixed wastewater, and also meaning that the nonreactive phosphorus will make up a larger percentage, so residuals are a better tool for comparison. In summary, lower residuals can be achieved, reflecting slightly lower percentage removal rates for total phosphorous with similar coagulant dosing rates without the use of a polymer.

Using the dosing ranges suggested by Shestakova *et al.* (2020) and the yearly influent phosphorous concentration from Öresundsverket (2020), mixed wastewater would need a dosing range of 9 to 14 mg Fe^{3+} /L or between 4 and 7 mg Al^{3+} /L at a minimum. When chemical additions to influent greywater are within these minimum ranges, a removal percentage increase of over 50% can be seen. This dosing would also be added to 70% of the water volume, meaning that chemical addition rates would stay the same but use would decrease by 30%, leading to possible cost reduction.

Like seen in Figure 6.3 with total phosphorus, Figure 6.4 shows that COD follows a trend where a minimum is reached and the efficacy of coagulation after that point starts to go down significantly as the residual concentrations increase. This upward trend in residual concentration at high doses is not as abrupt for COD as it is for total phosphorous and the minimum achievable COD concentration seems to occur at higher doses compared to the minimum total phosphorous concentration.

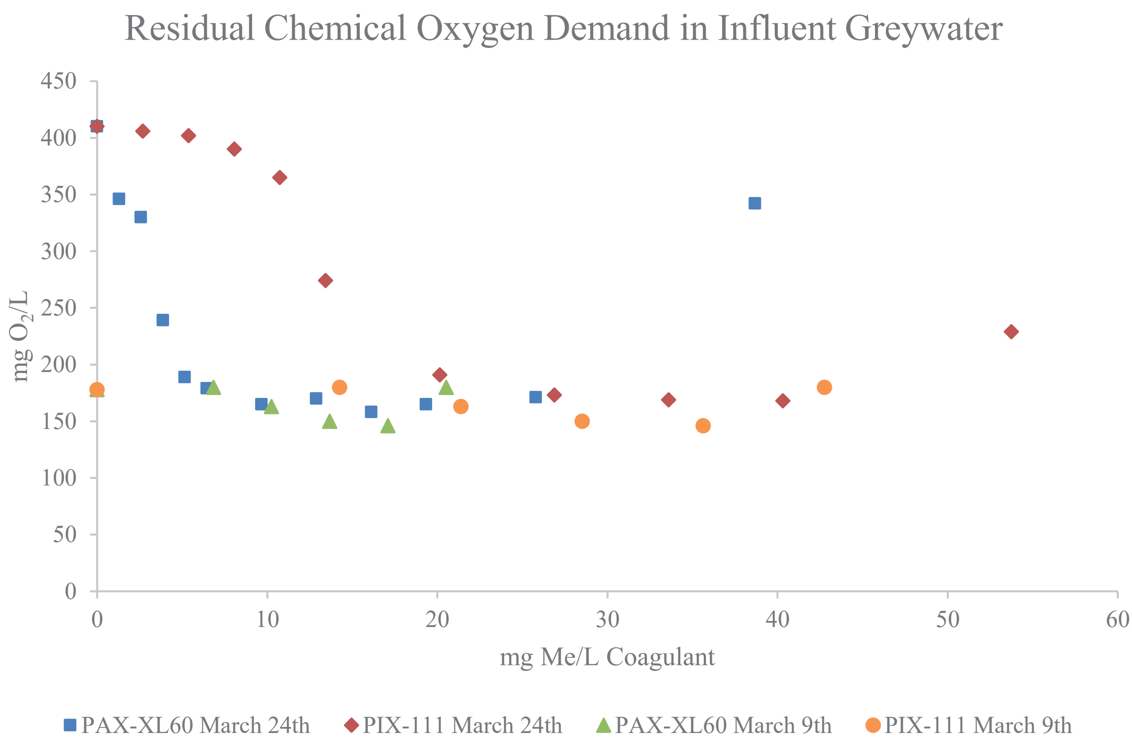


Figure 6.4 Residual Chemical Oxygen Demand after Coagulation in Influent Greywater

PAX-XL60 seems to perform better at lower doses than PIX-111 and was shown to achieve slightly lower residual COD than PIX-111. The sampling event on March 9th showed a minimum achievable concentration of 129 mg O_2/L COD for PAX-XL60 and 146 mg O_2/L for PIX-111 while the event on March 24th showed a minimum achievable concentration of 158 mg O_2/L COD for PAX-XL60 and 168 mg O_2/L for PIX-111. Removal rates peaked at 70% when a molar ratio of 12.5 or 17 mg Al^{3+}/L PAX-XL60 was added and 67% for both 12.5 and 15 molar ratios (35 and 40 mg Fe_{tot}/L) for PIX-111. Removal rates of 50% were exceeded with a molar ratio of 3 (4 mg Al^{3+}/L) for PAX-XL60 and 5 (14 mg Fe_{tot}/L) for PIX-111. This is some improvement over the removal due to settling alone of 20% but is not as pronounced as seen in total phosphorous removal. When comparing to the study by Väänänen *et al.* (2016), removal percentages are similar while the minimum achievable dose in greywater is around 150 mg O_2/L compared to a range between 50 to 200 mg O_2/L in mixed wastewater that is expected when mixed wastewater is dosed at 5-20 mg Al^{3+}/L or 10-30 mg Fe^{3+}/L.

Figure 6.5 shows the effect that dosing had on turbidity. Turbidity follows a similar pattern to total phosphorus in the beginning with a quick drop and leveling off around 5 mol coagulant per mol total phosphorus. However, after the level region, a clear deviation is seen for PIX-111 and PAX-XL60.

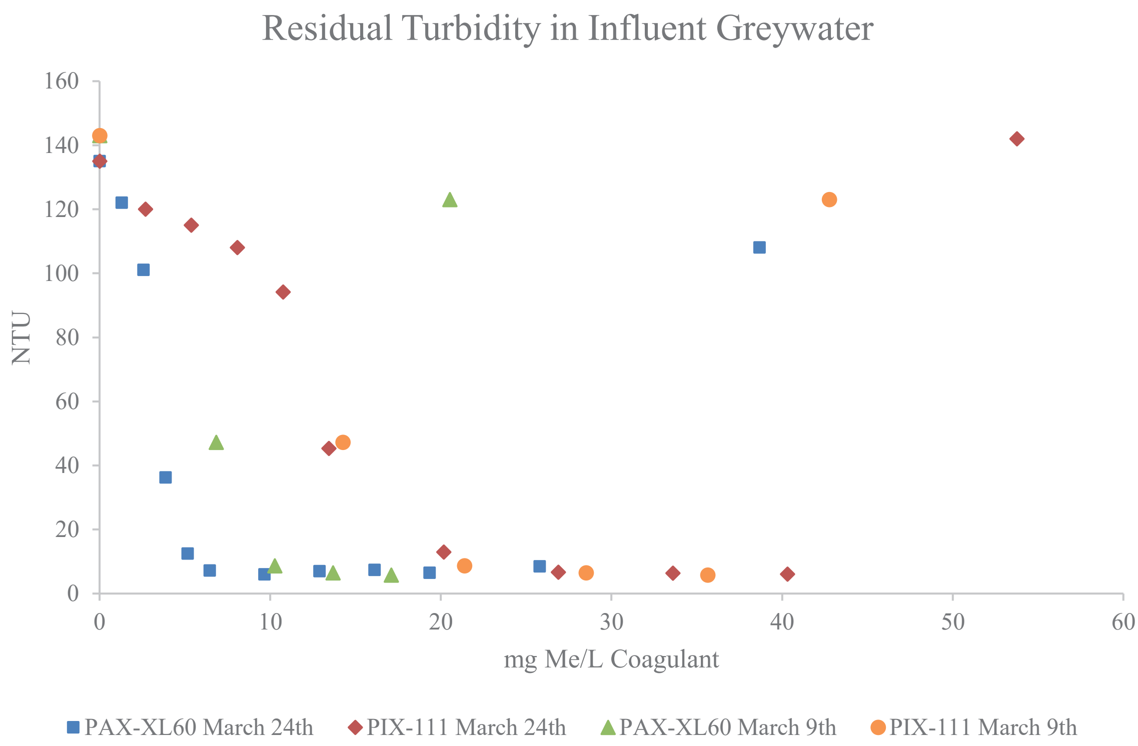


Figure 6.5 Residual Turbidity after Coagulation in Influent Greywater

While PAX-XL60 remains low at a molar ratio of 20 (26 mg Al^{3+}/L), PIX-111 changes drastically to a higher turbidity before they converge again around a molar ratio of 30 (81 mg Fe_{tot}/L for PIX-111 and 40 mg Al^{3+}/L for PAX-XL60), although still at a high turbidity, similar to that of the one observed at lower molar ratios. This deviation is likely due to the rust coloration created by the overdosing of PIX-111 and was retested to ensure accuracy. The high turbidity for both at high molar ratios is likely due to the excess positive ions present, inhibiting floc formation.

6.2 Chemical Precipitation in Biologically Treated Greywater

After jar testing PIX-111, there was no clear indication that the higher doses of coagulant had reached the same point of inefficacy as seen in the influent greywater. The flocs formed at higher doses seemed to have better settling qualities than those below a molar ratio of 10. Although settling was not very drastic in lower doses, it was still clear that the clarity of the water was not noticeably affected until around a molar ratio of 7.5 with the rust color becoming less noticeable at a molar ratio of 12.5. Figure 6.6 shows the jar tests during slow mixing and after 30 minutes of settling. There is a substantial jump in settling from a molar ratio of 20 to 30. During the March 9th sampling event settling was similar to that seen in the 30 molar ratio point but regrowth of sludge after the washout event between the 9th and 24th likely changed the settling characteristics and volume of sludge to be settled so jar tests from the 9th are therefore not pictured.

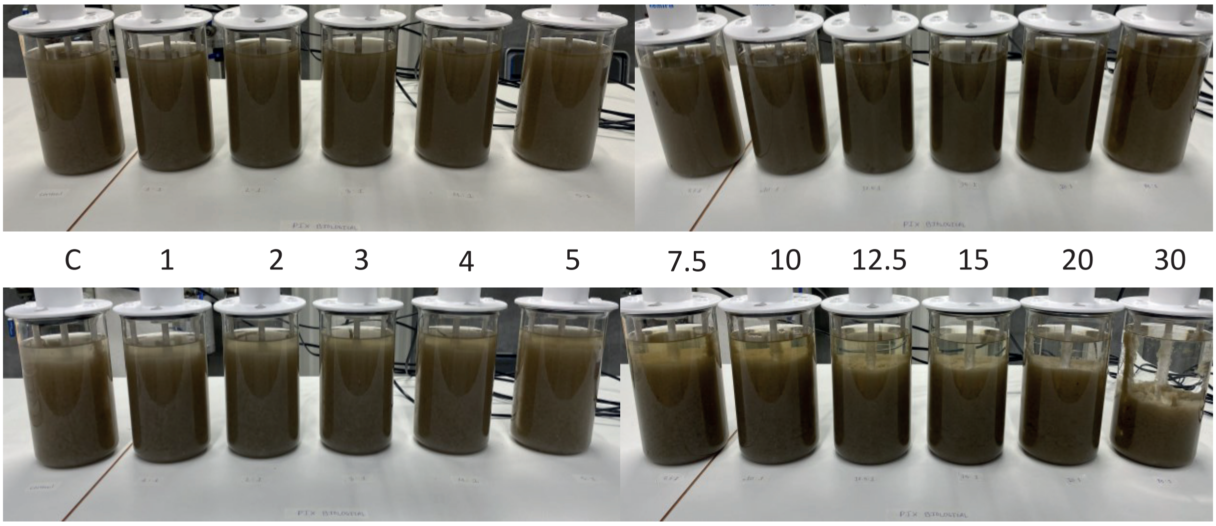


Figure 6.6 Jar Test for biologically treated greywater using PIX-111 during slow mixing (upper) and after settling for 30 minutes (lower). Molar ratios listed in between the two timepoints.

Jar tests at the same dosing points were repeated with PAX-XL60. Molar ratios of 7.5 and above had about the same effect on visual water clarity while better settling started at a molar ratio of 20 for PAX-XL60. Settling was also poor for this set but larger floc formation was noticeable when comparing PAX-XL60 to PIX-111. The jars during slow mixing and after 30 minutes of settling can be seen in Figure 6.7.

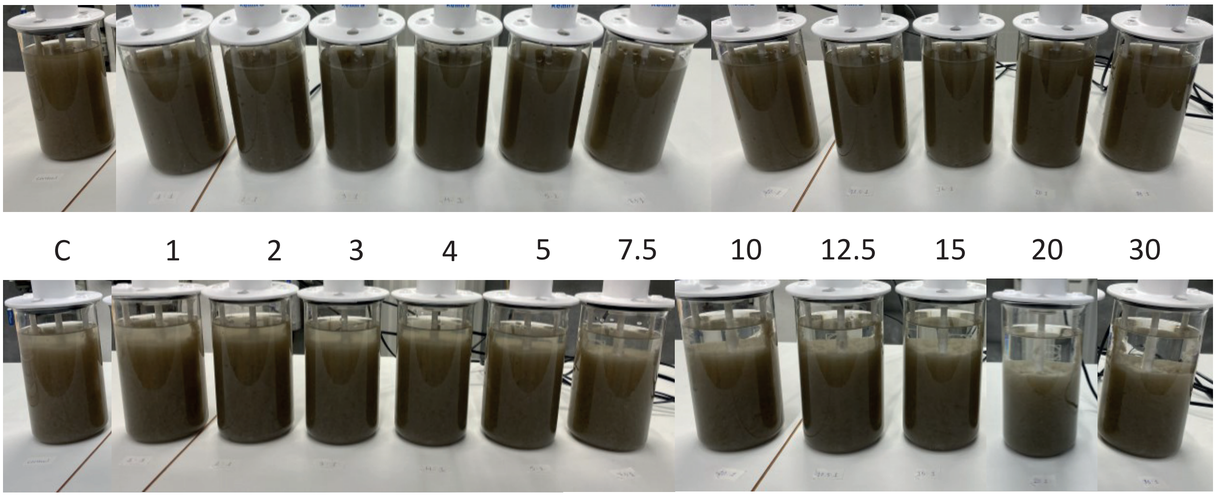


Figure 6.7 Jar Test for biologically treated greywater using PAX-XL60 during slow mixing (upper) and after settling for 30 minutes (lower). Molar ratios listed in between the two timepoints.

Since the biologically treated water was collected prior to settling, there was a large amount of preexisting suspended solids. The sampling bottle was shaken before pouring water into each jar and enough water was taken to avoid pouring all of the water from a bottle into a jar to reduce variation in suspended solids formation. However, variation still existed and could affect the required molar ratio doses. The presence of more suspended solids in general is likely why the molar ratio concentrations tended to be more effective at higher molar ratios in biologically treated water than influent water. It is important to note that RecoLab had experienced sludge loss prior to the start of sampling. Therefore, this water may not be the most representative of actual operating conditions since sludge concentrations varied between the two sampling events as sludge levels started to recover. The timeline of sampling events and sludge washout can be seen in Figure 5.1. Return sludge for the three months prior to the start of this project averaged around 6000 mg/L suspended solids. Starting on February 2nd, this dropped to 2500 mg/L and continued dropping until March 2nd to 1360 mg/L. On March 9th, the suspended solids count was 1960 mg/L. By the 21st, the return sludge had a suspended solids concentration of 2620 mg/L. This sludge concentration increase might have improved the effectiveness of biological nutrient removal and also changed the suspended solids to phosphorous ratio, leading to different chemical additions than the ones found in this study when the biological process is working as intended.

Table 6.3 shows the characteristics of greywater exiting the biological stage of treatment for both sampling events. In biologically treated greywater, the total phosphorous concentration was found to be 0.505 mg P/L with a COD concentration of 97 mg O_2/L and a turbidity in excess of 1000 NTU on March 9th. Both COD and total phosphorous saw no reduction due to settling on the 9th. On March 21st, sludge was even lower and total phosphorous was measured at 0.833 mg P/L. COD was 138 mg O_2/L and turbidity was still in excess of 1000 NTU. The treated control on March 21st showed that settling removed 43% of the total phosphorous and 74% of the COD. This drastic difference in removal due to settling is likely because of differences in sludge levels between the two events. Table 6.4 shows the mg Me/L additions for each molar ratio.

Table 6.3 Characteristics of greywater after exiting the biological stage of treatment before experimentation (untreated) and after laboratory settling (treated control).

Parameter	2022-03-09	2022-03-24
Untreated		
TP (mg P/L)	0.505	0.833
COD (mg O_2/L)	97	517
Turbidity (NTU)	> 1000	>1000
Treated Control		
TP (mg P/L)	0.462	0.475
COD (mg O_2/L)	100	134
Turbidity (NTU)	98	39

Table 6.4 Molar ratios as mg Me/L metal added to biologically treated greywater.

Molar ratio (Molar ratio to influent TP)	**2022-03-09**		**2022-03-24**	
	PIX-111 mg Fe_{tot} /L	**PAX-XL60 mg Al^{3+}/L**	**PIX-111 mg Fe_{tot} /L**	**PAX-XL60 mg Al^{3+}/L**
0	0	0	0	0
1 (0.6)	-	-	1.5	0.7
2 (1.1)	-	-	3.0	1.5
3 (1.7)	-	-	4.5	2.2
4 (2.3)	-	-	6.1	2.9
5 (2.8)	-	-	7.6	3.6
7.5 (4.2)	-	-	11	5.4
10 (5.6)	-	-	15	7.3
12.5 (7.0)	-	-	19	9.1
15 (8.4)	-	-	23	11
20 (11.3)	18	9.0	30	15
30 (16.9)	28	13	45	22
40	37	18	-	-
50	47	22	-	-
60	56	27	-	-
70	-	31	-	-

The difference in measured total phosphorous concentrations in biologically treated water between the two events was somewhat significant, about 1.7 as concentrated on the 21st as the 9th. Because of that, the molar ratios and the equivalent mg Me/L added differ substantially between the two days. This highlights the challenges of working with low phosphorous concentrations in influent water. Small changes in concentrations are amplified because the percent change is more than if a similar value change were to occur at higher concentrations. Therefore, the dosing above can be used as a guide but not a rule since water will vary from the concentrations used. With more sampling events, operating ranges could be established, but with the current results, it is hard to determine if these coagulant additions would remain effective over the normal variations in influent water.

As seen in Figure 6.8, PAX-XL60 makes total phosphorous undetectable at a molar ratio of 20 (8-15 mg Al^{3+}/L) while PIX-111 does not achieve this until after a molar ratio dose of 30 (30-45 mg Fe_{tot}/L). Two values were removed at very high molar ratios from the above graph due to the high likelihood that pieces of floc were included within the sample and retesting that confirmed there was an analytical error. The trend appears to start off linear, then has an increasing efficacy rate until around a molar ratio of 10 (7 mg Al^{3+}/L) for PAX-XL60 and slightly after 10 (15 mg Fe_{tot}/L) for PIX-111 where it begins to slow down again and level out before becoming undetectable. An important note is that PAX-XL60 seems to work more effectively and remove more total phosphorous at lower doses than PIX-111. Both PIX-111 and PAX-XL60 reached the maximum detectable removal rate of 94% from the initial measured concentration in biologically treated water and 97% removal of what entered in the influent water by a molar ratio of 15 (11 mg Al^{3+}/L) for PAX-XL60 and 20 (30 mg Fe_{tot}/L) for PIX-111 compared to a removal rate of 43% from settling alone. Removal rates close to 90% of the influent concentration were achieved at a molar ratio of 10 (7 mg Al^{3+}/L) for PAX-XL60 and 12.5 (19 mg Fe_{tot}/L) for PIX-111.

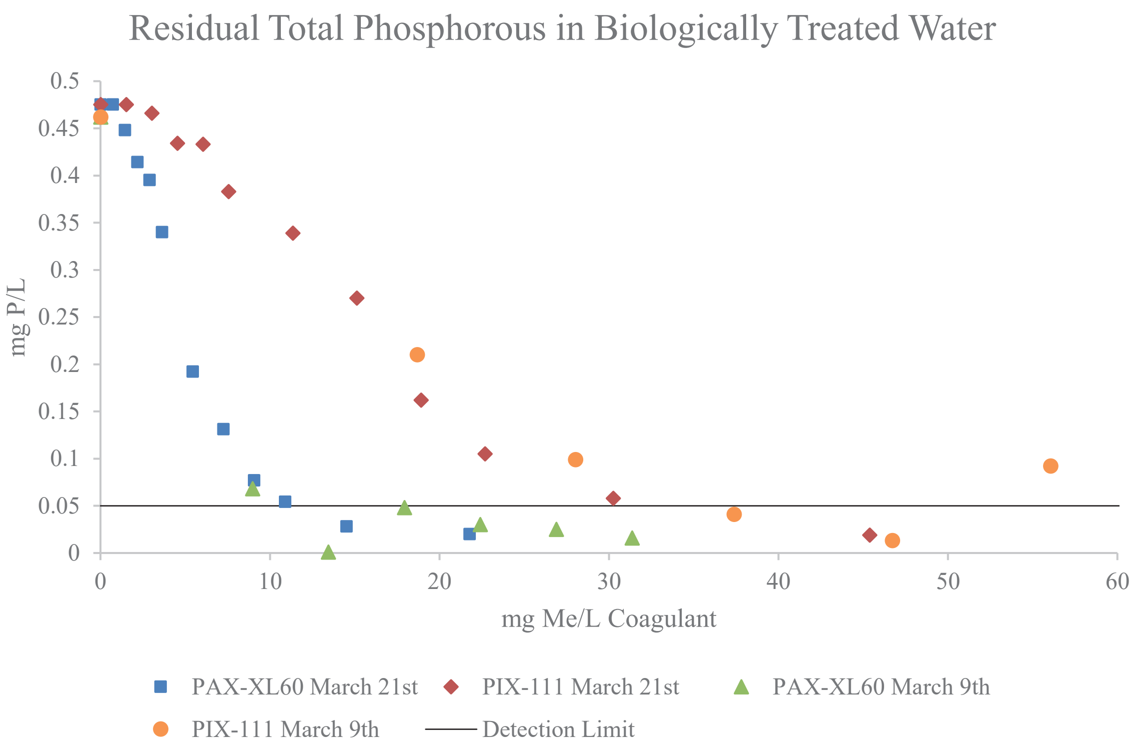


Figure 6.8 Residual Total Phosphorous Concentration after Coagulation in Biologically Treated Greywater. The line at 0,05 mg P/L indicates the detection limit of the Hach Lange cuvettes used. All values below the line are considered undetectable even though a numerical reading was obtained

Langer *et al.* (2017) showed that effluent total phosphorous concentrations right above 0.05 mg/L can be achieved during tertiary treatment with coagulant doses as low as 3 mg Al^{3+}/L and 1.5 mg/L of a polymer flocculant. This corresponded to an overall removal of total phosphorous around 90%. While a direct comparison is hard to make since wastewater used by Langer *et al.* (2017) had a suspended solids concentration as low as 5-10 mg/L and the biologically treated greywater had a suspended solids concentration closer to 2000 mg/L, similar residual total phosphorous concentrations can be achieved with unsettled biologically treated water at doses around 10 mg Al^{3+}/L for PAX-XL60 and 20 mg Fe_{tot}/L for PIX-111.

As indicated prior, a dosing range of 9 to 14 mg Fe^{3+} /L or between 4 and 7 mg Al^{3+} /L were minimum coagulant requirements laid out in About Water Treatment (Shestakova *et al.*, 2020) with the caveat that many factors increase this requirement, including the intention of very low residual phosphorus. Considering this, chemical additions would need to be slightly higher than the minimum requirements for mixed wastewater based on influent total phosphorous concentrations but phosphorous removal would be well below the required removal rates and the proportion of water treated would decrease by 30%. Since the required molar ratio for simultaneous precipitation in this mixed wastewater is unknown, the chemical requirements are hard to compare exactly and no prediction on the effect on cost could be made.

Figure 6.9 shows that COD follows a similar pattern to total phosphorous but the initial linear zone is less pronounced, especially in samples dosed with PIX-111. Even at high doses, COD continues to decrease but at a much slower rate than seen at the peak rate of decrease, around molar ratios of 5 through 10 (4-7mg Al^{3+}/L PAX-XL60 and 8-15 mg Fe_{tot}/L PIX-111). This occurs at slightly lower doses compared the largest jump in residual total phosphorous but the trends are still similar.

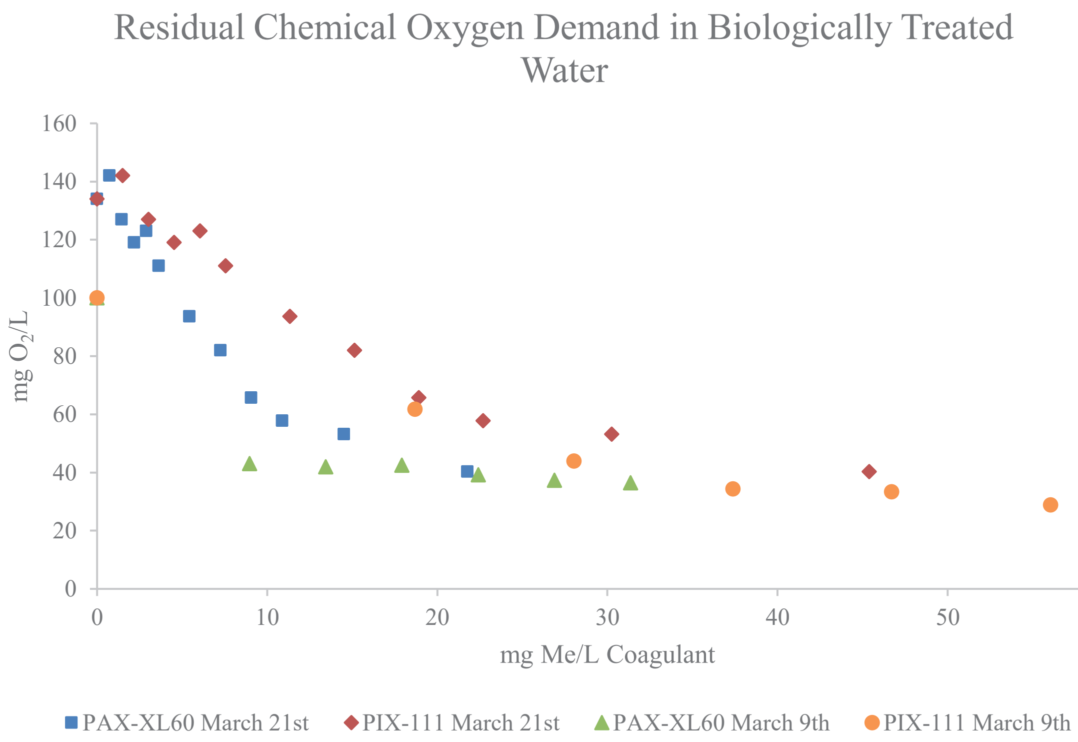


Figure 6.9 Residual Chemical Oxygen Demand after Coagulation in Biologically Treated Greywater.

PIX-111 does not seem to be as effective at removing COD at low doses compared to PAX-XL60 but might be more effective at higher doses. PAX-XL60 removes more COD at lower doses, the same trend seen in total phosphorous, and begins to level off as COD approaches 30 mg O_2/L. PIX-111 follows a similar pattern, with the lowest observed COD concentration at a molar ratio of 60 (56 mg Fe_{tot}/L) with a concentration of 29 mg O_2/L COD. Although settling alone appears to remove almost 75%, when dosed at a ratio of 15 (23 mg Fe_{tot}/L PIX-111 or 11 mg Al^{3+}/L PAX-XL60) or above, PAX-XL60 and PIX-111 can remove 90% of COD.

Like COD and total phosphorous, turbidity follows a similar S shape as seen in Figure 6.10. While the unsettled turbidity was above detection limits, the settled control was quite similar to that of the first few dosing points. Both PIX-111 and PAX-XL60 appeared to be equally effective at removing turbidity early on but PAX-XL60, as seen in both COD and total phosphorous, was better at removing turbidity at lower doses.

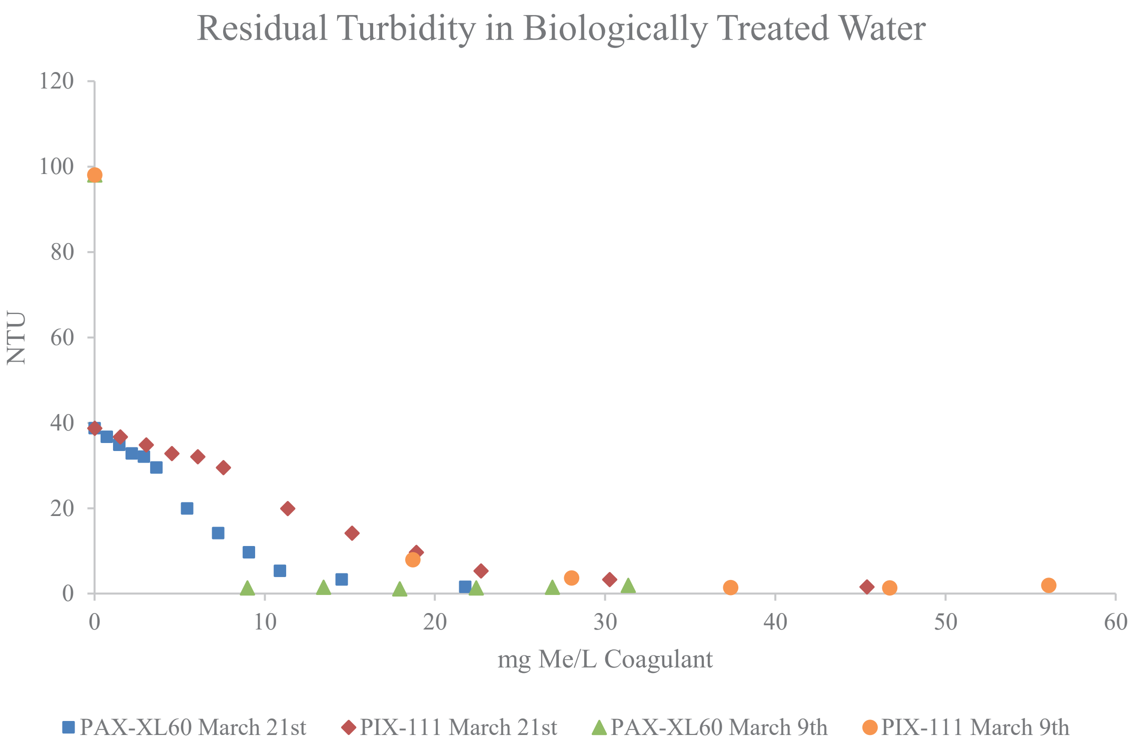


Figure 6.10 Residual Turbidity after Coagulation in Biologically Treated Greywater.

Overdosing PIX-111 can lead to tinting of water with a rust color that could cause turbidity to measure extremely high due to the addition of turbidity, not a residual of what was originally present. Similarly, lower doses of PIX-111 can tint the water slightly, but not as intensely. Regardless, both PIX-111 and PAX-XL60 dosed water decreases in turbidity as dosing was increased, leveling off at a minimum turbidity right above 1.0 NTU at higher doses.

6.3 Pre-Precipitation compared to Co-Precipitation or Post-Precipitation

As seen in all trends for both influent and biologically treated greywater, PAX-XL60 produces lower residuals of all parameters at lower doses compared to PIX-111. Additionally, greywater that has undergone the biological treatment step will need to be dosed at higher concentrations to achieve an extremely low concentration below a detection limit of 0.05 mg P/L, but it is achievable. Comparatively, influent greywater can only achieve around 0.2 to 0.3 mg P/L. For both total phosphorous and turbidity, the residual concentration in influent and biologically treated greywater becomes about the same when a molar ratio around 7.5 to 10 is used, with biologically treated greywater continuing to decrease while influent greywater tends to decrease, level off, and increase again. With COD, the biologically treated greywater always achieved a lower concentration from the same molar ratio, regardless of the mg/L dose. Additionally, at these concentrations the percentage of total phosphorous removal may not be the best measure of removal. A lower concentration of phosphorus in water exiting the biological stage means that lower concentrations can be achieved with lower coagulant doses when measured in mg Me/L. When considering the higher molar ratios used in biologically treated water, the mg Me/L concentration tends to be about the same as a dose half as concentrated than the same molar ratio in influent water. This makes the coagulant addition required smaller in biological treatment as opposed to the influent stream, even when considering the suspended solids and larger competition for reaction with coagulants. So, the volume of chemicals required in co-precipitation or post-precipitation in the case of Östra Ramlösa (where there is no sludge return) is lower or similar and achieves lower phosphorous and COD concentrations than pre-precipitation in greywater.

6.4 Implications for Biological Treatment

Because the coagulation processes considered are done prior to the biological step or could be recycled into the biological step, the ratio of COD to phosphorous is an important consideration when dosing. Krishnan *et al.* (2008) showed that aerobically treated greywater achieved the lowest residual concentrations of contaminants when a COD:N:P nutrient ratio of 100:5:1 was maintained with a retention time of 36 hours. This was the highest nutrient ratio tested because it has been long accepted as the optimum ratio for aerobic suspended biological treatment. A similar standard of 250:5:1 (100:2:0.4) is accepted for use in anaerobic suspended biological treatment. None of the greywater tested in this study from either water type at any molar ratio achieved either of these ratios, as seen in Table 6.5. However, Tay *et al.* (2003) found that a ratio of 300:5:1 (100:1.67:0.33) was most effective in fixed bed bioreactors, which function similar to moving bed bioreactors (MBBR) like the one considered for use in Östra Ramlösa. Table 6.5 shows the nutrient ratios that met these MBBR requirements with their respective molar ratio and mg Me/L doses.

Table 6.5 Selected Ratios that met MBBR requirements

Water Type	Coagulant	Molar ratio	mg Me/L	COD:TN:TP
Influent		Control	-	100:16:0.31
	PAX-XL60	1:1	1.3	100:13:0.35
		2:1	2.6	100:12:0.34
Biological		Control	-	100:30:0.35
	PAX-XL60	1:1	0.7	100:24:0.36
		2:1	1.5	100:25:0.35
		3:1	2.2	100:20:0.36
		4:1	2.9	100:12:0.37
		5:1	3.6	100:20:0.36
	PIX-111	1:1	1.5	100:32:0.33
		2:1	3.0	100:28.0.36
		3:1	4.5	100:25:0.36
		4:1	6.1	100:23:0.35
		5:1	7.6	100:25:0.34
		7.5:1	11	100:17:0.36

In influent water, a nutrient ratio of 100:17:0.28 COD:TN:TP was observed, meaning that phosphorous is already a limiting factor in influent greywater. A similar circumstance is present in the activated sludge with an observed nutrient ratio of 100:19:0.16. For PAX-XL60 in biologically treated water, this nutrient ratio was improved in the control sample and with molar ratios from 1 to 10, being above or around the recommended ratio for fixed bed bioreactors until a molar ratio of 5 (3.6 mg Al^{3+}/L). PIX-111 is similar with an improved nutrient ratio for all but molar ratios of 20 and 30 and a favorable nutrient ratio until a molar ratio of 10 (15 mg Fe_{tot}/L). In influent water, the nutrient ratio improves during the control and the lowest two molar ratios of 1 and 2 for PAX-XL60 but fails to meet a favorable nutrient ratio at all using PIX-111.

Nitrogen concentrations were calculated and considered but they were never the limiting factor in the COD:N:P ratio and did not change to a noticeable degree due to precipitation. This means that the only limiting factor is phosphorus. Considering the data from Table 6.5, pre-precipitation poses risks of limiting the efficacy of biological treatment very quickly in an activated sludge-based treatment. This risk is less so when considering MBBR because chemicals are added after the greywater has left the biological stage and no coagulant-containing sludge will return to the biological process. It therefore functions more as post-precipitation compared to co-precipitation. However, all greywater failed to meet the long-time nutrient ratio standards for aerobic and anaerobic sludge processes in mixed wastewater. When considering RecoLab, the risk of precipitating too much phosphorous is also present in co-precipitation because sludge is returned to the chamber and any residual coagulant could react with phosphorous and act to increase the effective coagulant dose in the biological stage. This risk is not of concern for the proposed design at Östra Ramlösa since MBBR does not require a return sludge stream, so dosing and precipitation could be pushed further. However, since Östra Ramlösa will use a constructed wetland and spray filters, some biological growth is expected after the biological step so consideration of biologically available phosphorous must be given.

In conclusion, none of the nutrient ratios are favorable for any form of biological treatment except MBBR and phosphorous is the limiting factor. PAX-XL60 can be used in influent greywater in very low concentrations without creating an unfavorable nutrient ratio for MBBR while both PIX-111 and PAX-XL60 can be used in biologically treated water at molar dosing ratios up to 5 (8 mg Fe_{tot} /L and 4 mg Al^{3+}/L).

7 Conclusions

Where to place treatment, residual concentrations, coagulant dosing, coagulant types, and the effect that chemical precipitation had on nutrient ratios and the subsequent effect on nutrient removal during biological treatment were all studied to better understand how chemical precipitation of phosphorous can be applied to source separated greywater treatment.

Laboratory jar tests have shown that phosphorous concentrations can be reduced to less than 0.2 mg P/L in influent greywater with the addition of coagulants, corresponding to a removal rate of around 85% total phosphorous. If co-precipitation or post-precipitation on unsettled biologically treated water is used, phosphorous concentrations can be reduced below detection limits (0.05 mg P/L) at high doses, accounting for a detectable removal of >90% of influent phosphorous concentrations.

Realistically, coagulant addition will occur at molar ratios between 1 and 5. This corresponds to 1.5-13 mg Me/L of coagulant in the influent and 0.5 to 8 mg Me/L in biologically treated water, which are very similar to the doses used in mixed wastewater to achieve higher residual concentrations. Phosphorous removal rates at doses between 1.5 and 13 mg Me/L in influent greywater and 0.5-8 mg Me/L in biologically treated water were up to 80% in influent water, achieving concentrations of 0.31 mg P/L in the residual for PAX-XL60 and 0.63 mg P/L for PIX-111. In biologically treated water, final phosphorous concentrations were about the same at identical molar ratios, but if similar mass dosing was used, residual phosphorous becomes undetectable (<0.05 mg P/L). Of the two, PAX-XL60 showed better removal at lower concentrations and does not add rust color to the water. Without price consideration, the results of this study indicate it to be the better choice.

Because concentrations become so low and the COD:N:P nutrient ratio in the influent greywater stream is already phosphorous limiting for biological treatment, pre-precipitation introduces a risk of removing too much phosphorous and diminishing the efficacy of biological treatment. Co-precipitation allows for similar removal rates to be achieved with half the dosing. If the chemical is added near the end of the biological stage, the risk of removing too much phosphorous via precipitation is decreased. Since return sludge will likely contain residual coagulant that will diminish the nutrient ratio, it could negatively affect the biological treatment stage and needs to be considered when dosing. It can also increase solids loading so clarifier capacity should be checked before implementation of co-precipitation. Furthermore, it could also limit the ability to certify sludge for reuse since the chemical and biological sludge are combined. In the instance of MBBR this concern is removed since no return sludge is required. Considering that no additional basins are needed and the chemical requirement for co-precipitation is smaller than that of pre-precipitation, co-precipitation appears to be a better option for RecoLab. Dosing at the same spot at Östra Ramlösa is still advantageous but due to the lack of a return sludge stream with MBBR, it will function more similar to post-precipitation and is considered as such. It is still more advantageous than pre-precipitation and is also the better option for Östra Ramlösa.

8 Future Work

Because of the wash out event that occurred in the early stage of this project, an additional study on the biologically treated water could be carried out once the biological sludge has had time to adapt itself to greywater. Expanding the types of coagulants tested could also help determine which coagulant characteristics are optimum for greywater and if they differ significantly than those from mixed wastewater. Looking at the addition of polymers to aid in the coagulation and flocculation process would also be interesting to investigate when applied to greywater. Once the Östra Ramlösa plant is completed and microbial characteristics are established, a study on that plant, where EBPR is not intended would be useful in understanding the role of precipitation in phosphorous removal in a more general, and more commonly used setting. A study on the use of post-precipitation in greywater treated with an activated sludge system could also be helpful in determining the cost/benefit tradeoffs between chemical costs, additional basins, resource recovery, and sludge certification. A study looking at the fractionation of total phosphorous, phosphates, nonreactive, and biologically available phosphorous would also help to further understand what remains and what methods are available to remove the residual if future demands require it.

9 References

Arinaitwe, E. C. 2018. *Suitable treatment of source separated greywater for dischage into an Urban Environment.* M.Sc.Eng., Lund University.

Boyjoo, Y., Pareek, V. K. & Ang, M. 2013. A review of greywater characteristics and treatment processes. *Water Science and Technology,* 67**,** 1403-1424.

Chrispim, M. & Nolasco, M. 2016. Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil. *Journal of Cleaner Production,* 142.

Dallas, S., Scheffe, B. & Ho, G. 2004. Reedbeds for greywater treatment—case study in Santa Elena-Monteverde, Costa Rica, Central America. *Ecological Engineering,* 23**,** 55-61.

Davis, M. L. 2010. *Water and Wastewater Engineering: Design Principles and Practice,* New York, McGraw-Hill Education 9780071713849.

Dixon, A., Butler, D., Fewkes, A. & Robinson, M. 2000. Measurement and Modelling of Quality Changes in Stored Untreated Grey Water. *Urban Water,* 1**,** 293-306.

Du, Y., Ramirez, C. E. & Jaffé, R. 2018. Fractionation of Dissolved Organic Matter by Co-Precipitation with Iron: Effects of Composition. *Environmental Processes,* 5**,** 5-21.

Edwin, G. A., Gopalsamy, P. & Muthu, N. 2014. Characterization of domestic gray water from point source to determine the potential for urban residential reuse: a short review. *Applied Water Science,* 4**,** 39-49.

Eriksson, E., Auffarth, K., Henze, M. & Ledin, A. 2002. Characteristics of grey wastewater. *Urban Water,* 4**,** 85-104.

Finnson, A. 2022. *Aktivt uppströmsarbete med Revaq-certifiering* [Online]. SvensktVatten. Available: https://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/kretslopp-och-uppstromsarbete/revaq-certifiering/ [Accessed 04-20 2022].

Friedler, E. & Alfiya, Y. 2010. Physicochemical treatment of office and public buildings greywater. *Water Science and Technology,* 62**,** 2357-2363.

Fundneider, T., Alejo, L. & Lackner, S. 2020. Tertiary phosphorus removal to extremely low levels by coagulation-flocculation and cloth-filtration. *Water Science and Technology,* 82**,** 131-143.

Ghaitidak, D. M. & Yadav, K. D. 2016. Greywater treatment for reuse: comparison of reuse options using analytic hierarchy process. *Journal of Water Reuse and Desalination,* 6**,** 108-124.

Ghunmi, L. A., Zeeman, G., Fayyad, M. & Van Lier, J. B. 2011. Grey Water Treatment Systems: A Review. *Critical Reviews in Environmental Science and Technology,* 41**,** 657-698.

Jefferson, B., Burgess, J. E., Pichon, A., Harkness, J. & Judd, S. J. 2001. Nutrient addition to enhance biological treatment of greywater. *Water Research,* 35**,** 2702-2710.

Jefferson, B., Palmer, A., Jeffrey, P., Stuetz, R. & Judd, S. 2004. Grey water characterisation and its impact on the selection and operation of technologies for urban reuse. *Water Science and Technology,* 50**,** 157-164.

Jenssen, P. D. 2005. Decentralized urban greywater treatment at Klosterenga Oslo. *Ecological engineering- bridging between ecology and civil engineering.* The Netherlands: Æneas Technical Publishers 90-75365-71-3.

Kasak, K., Karabelnik, K., Kõiv, M., Jenssen, P. D. & Mander, Ü. 2011. Phosphorus removal from greywater in an experimental hybrid compact filter system. *Water Resources Management VI,* 145.

Krishnan, V., Ahmad, D. & Jeru, J. B. 2008. Influence of COD:N:P ratio on dark greywater treatment using a sequencing batch reactor. *Journal of Chemical Technology & Biotechnology,* 83**,** 756-762.

Kängsepp, P., Sjölin, M., Mutlu, A. G., Teil, B. & Pellicer-Nàcher, C. 2020. First full-scale combined MBBR, coagulation, flocculation, Discfilter plant with phosphorus removal in France. *Water Practice and Technology,* 15**,** 19-27.

Langer, M., Väänänen, J., Boulestreau, M., Miehe, U., Bourdon, C. & Lesjean, B. 2017. Advanced phosphorus removal via coagulation, flocculation and microsieve filtration in tertiary treatment. *Water Science and Technology,* 75**,** 2875-2882.

Li, F., Wichmann, K. & Otterpohl, R. 2009. Review of the technological approaches for grey water treatment and reuses. *Science of The Total Environment,* 407**,** 3439-3449.

Metcalf & Eddy, I. 1991. *Wastewater Engineering: Treatment , Disposal, and Reuse*, McGraw-Hill Education 9780070418783.

Miljödepartementet 2014. Kronologi över viktiga miljöhändelser i Sverige: mars 2004—mars 2014. 103 33 Stockholm: Regeringskansliet.

Morling, S. 2019. Swedish Experience and Excellence in Wastewater Treatment Demonstrated Especially in Phosphorus Removal. *Journal of Water Resource and Protection,* 11**,** 333-347.

Naturvårdverket 1995. *Vad innehåller avlopp från hushåll?,* Stockholm, Naturvårdsverket 91-620-4425-7.

Nolde, E. 2000. Greywater reuse systems for toilet flushing in multi-storey buildings – over ten years experience in Berlin. *Urban Water,* 1**,** 275-284.

Noutsopoulos, C., Andreadakis, A., Kouris, N., Charchousi, D., Mendrinou, P., Galani, A., Mantziaras, I. & Koumaki, E. 2018. Greywater characterization and loadings – Physicochemical treatment to promote onsite reuse. *Journal of Environmental Management,* 216**,** 337-346.

Olsson, K., Persson, L.-I., Thysell, U., Landsbo, A. & Öreberg, S. 2013. Smarta system och listiga lösningar — Ställningstagande utifrån rapporten Möjligtheternas H+, samorning av de tekniska resursflöena energi, vatten, avlopp, och avfall (EVVA), Etapp 2. *In:* STAD, H., NSR, NSVA & ÖRESUNDSKRAFT (eds.). Helsingborg.

Palmquist, H. & Hanaeus, J. 2005. Hazardous substances in separately collected grey- and blackwater from ordinary Swedish households. *The Science of the total environment,* 348**,** 151-63.

Pidou, M., Avery, L., Stephenson, T., Jeffrey, P., Parsons, S. A., Liu, S., Memon, F. A. & Jefferson, B. 2008. Chemical solutions for greywater recycling. *Chemosphere,* 71**,** 147-155.

Pidou, M., Memon, F. A., Stephenson, T., Jefferson, B. & Jeffrey, P. 2007. Greywater recycling: treatment options and applications. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability,* 160**,** 119-131.

Ridderstolpe, P., Fahlgren, T. F. & Lagerquist, K. 2021. Gråvattenrening för Östra Ramlösa - underlag till detaljprojektering.

Scherrenberg, S. M., Menkveld, H. W. H., Bechger, M. & Van Der Graaf, J. H. J. M. 2011. Minimising the risk on phosphorus limitation; an optimised coagulant dosage system. *Water Science and Technology,* 64**,** 1708-1715.

Shestakova, M., Hansen, B., Valanko, R., Pekonen, P., Hesampour, M., Halttunen, S., Hofmann, R., Pretorius, R., Penttinen, M., Recktenwald, M., Karpova, T., Rossum, R., Grönfors, O., Mattsson, E., Ahlgren, J., Nilsson, B., Leen, P., Havansi, H. & Abinet, R. 2020. *About Water Treatment,* ISBN 978-951-97173-8-8 (hardcopy) ISBN 978-951-97173-9-5 (digital).

Šostar-Turk, S., Petrinić, I. & Simonič, M. 2005. Laundry wastewater treatment using coagulation and membrane filtration. *Resources, Conservation and Recycling,* 44**,** 185-196.

Tay, J.-H., Chui, P.-C. & Li, H. 2003. Influence of COD:N:P Ratio on Nitrogen and Phosphorus Removal in Fixed-Bed Filter. *Journal of Environmental Engineering,* 129**,** 285-290.

Tooker, N., Guswa, S., Horton, J., Hastings, M. & Devalk, C. 2010. Pilot testing for low-level phosphorous removal:confronting non-reactive phosphorous challenges. *Proceedings of the Water Environment Federation,* 16**,** 959-975.

Väänänen, J. 2014. *Applying coagulation, flocculation and discfiltration in tertiary treatment.* Thesis - Licentiate thesis.

Väänänen, J. 2017. *Microsieving in municipal wastewater treatment : Chemically enhanced primary and tertiary treatment.* Thesis - Doctoral thesis (compilation), Department of Chemical Engineering, Lund University.

Väänänen, J., Cimbritz, M. & La Cour Jansen, J. 2016. Microsieving in primary treatment : Effect of chemical dosing. *Water Science and Technology,* 74**,** 438-447.

Öresundsverket 2020. Miljörapport 2020. Helsingborgs Kommun.

10 Appendix: Popular Science Summaries

10.1 Popular Science Summary

Three Pipes Out

How source separation is changing the way we think about wastewater.

As we move to a more sustainable world, the systems we have used for many years are starting to change. A prime example of this is Helsingborg, Sweden. A new city district called Oceanhamnen has been designed with sustainability in mind by using a source separated wastewater system. Residence of the neighborhood experience life a bit differently. Food grinders have replaced the paper bag system for food waste disposal and vacuum toilets can be found in the bathrooms, although they are a far cry from their airplane counterparts. However, these changes are minor compared to those that have taken place underground and at the wastewater treatment plant. Instead of one pipe leaving the building, three do. One contains food waste from the kitchen sink, another contains water from the toilet, and the third contains all other wastewater from wash basins, showers, and laundry machines. This third water type has come to be known as *greywater*. It accounts for more than 70% of the volume of water while only containing around 30% of the pollution. Because of this, we can treat greywater in a way that removes the most concerning contamination, like excess nitrogen and phosphorous, to extremely low concentrations.

If you have ever seen a lake turned green or smelled rotting water, you know the importance of treating water correctly. *Eutrophication* is responsible for the coloration and smell you might encounter. When too many nutrients enter waterways, it allows for more and more algae to grow. As the algae grows, it uses up all the available oxygen and begins to die, decomposing and creating that characteristic smell. Dividing wastewater into separate streams allows us to better remove these nutrient and prevent eutrophication.

For greywater, the treatment technology looks quite similar to traditional wastewater but different types of phosphorous present can affect which technologies are effective at removing it. The addition of special chemicals called *coagulants* helps to remove even more contamination. The coagulants act as glue and hold individual particles together until the group gets too heavy and falls to the bottom. Since less phosphorus reacts with these chemicals in greywater, less coagulant need to be added. While this type of treatment is used in current wastewater treatment plants, source separation means that less water needs to be treated and fewer chemicals need to be added to remove the contamination present.

This study aimed to determine the best place to add coagulants, which coagulants to add, how much of them to add, and how much phosphorous can be removed. Results showed that similar amount of coagulant used in traditional wastewater plants can be used to remove phosphorous to extremely low levels. To remove 80% of the contamination present, the same concentration of coagulant needs to be added as what would remove around 30% in mixed wastewater. There is more removal observed when the coagulant is added near the end of treatment than right at the beginning. Better removal was also achieved when an aluminum-based chemical is used compared to an iron-based one. Other measures of water quality were also looked at, like water clarity and the potential to use up available oxygen. Both of these also saw improved removal rates in the same way that phosphorus did.

Oceanhamnen and its new wastewater system seems to be a success because a similar district is planned to be built in a more suburban setting in Helsingborg, called Östra Ramlösa. The results of this study will aid in the design and operation of new and similar plants to Oceanhamnen like Östra Ramlösa as we shift towards the future of infrastructure.

10.2 Populärvetenskaplig Sammanfattning

Tre Rör Ut

Hur källsortering förändrar vårt sätt att tänka kring avloppsvatten.

Allt eftersom vi går mot en mer hållbar värld, förändras systemen vi använt sedan länge också. Ett bra exempel på detta är Helsingborg, Sverige. En ny stadsdel som heter Oceanhamnen har utvecklats med stort fokus på hållbarhet och ett källsorterat avloppsvattensystem. Grannskapets invånare lever lite annorlunda där. Matkvarnar har ersatt papperspåsar för matavfall och vakuumtoaletter hittas i badrummen, men de här toaletterna är långt ifrån sina motsvarigheter som finns i flygplan. Däremot är dessa omställningar mindre än de förändringar som genomförts under markytan och på avloppsreningsverket. I stället för ett rör som lämnar huset, gör tre det. Det första röret innehåller matavfall från kökets diskbänk, det andra innehåller vatten från toaletten, och det tredje innehåller resterande avloppsvatten från handfaten, duschar, och tvättmaskiner. Den tredje vattentypen har kommit att kallas *gråvatten*. Gråvattnet står för mer än 70% av avloppsvattnets volym men innehåller ungefär 30% av föroreningarna. På grund av detta kan vi rena gråvatten på ett sätt som avskiljer de oroande föroreningarna, såsom överskott av kväve och fosfor, mot väldigt låga koncentrationer.

Om du någonsin har sett en sjö som blivit grön eller luktat som ruttet vatten, vet du hur viktig det är att rena vatten som släpps ut i den på rätt sätt. *Övergödning* är ansvarig för den färg och lukt man skulle kunna uppleva. När ett överskott av näringsämnen finns i vattnet, så växer mer och mer alger. När alger växer så använder de upp allt tillgängligt syre, när de sedan dör och bryts ned uppstår den karakteristiska lukten. Att dela upp avloppsvatten i olika fraktioner tillåter oss att bättre avskilja dessa näringsämnen och förhindra övergödning.

För gråvatten är reningstekniken ganska lik processer för traditionellt avloppsvatten, men olika typer av fosfor som finns kan påverka vilka teknologi är effektiva för att släppa ut det. Tillsatsen av särskilda kemikalier som kallas *koaguleringsmedel* hjälper till att avskilja större andel avföroreningarna. Koaguleringsmedlet fungerar som ett lim och håller individuella partiklar tillsammans tills partikelgruppen väger för mycket och faller mot botten. Eftersom mindre fosfor reagerar med dessa kemikalier i gråvatten behöver mindre koaguleringsmedel tillsättas. Källsortering skulle innebära att mindre mängder vatten skulle behöva renas och färre kemikalier behöver tillsättas för att avskilja föroreningarna.

Denna studie har försökt att bestämma var i reningsprocessen som koaguleringsmedlet skall tillsättas, vilka koaguleringsmedel som borde användas, hur stora mängder som bör tillsättas och hur mycket fosfor som kan avskiljas. Resultaten visade att liknande halter av koaguleringsmedel som används i traditionella avloppsreningsverk kan användas för att avskilja fosfor till väldigt låga koncentrationer i gråvatten. För att avskilja 80% av föroreningarna i gråvatten, behöver samma koncentration av koaguleringsmedel som skulle avskilja ungefär 30% i blandat avloppsvatten läggas till. Mer avskiljning observerades när koaguleringsmedlet lades till nära slutet av reningsprocessen jämfört med i början. Bättre avskiljning uppnåddes också när ett aluminium-baserat koaguleringsmedel användes jämfört med ett järn-baserat. Andra vattenkvalitetsparametrar undersöktes också, såsom vattnets klarhet och innehåll av syreförbrukande ämnen. Dessa parametrar förbättrades på samma sätt som fosforhalten genom koaguleringen.

Oceanhamnen och dess nya avloppsreningsverk verkar vara lyckat eftersom en liknade stadsdel planeras att byggas i en förortsmiljö i Helsingborg, nämligen Östra Ramlösa. Resultatet av den här forskningen kommer att vara användbar vid utveckling och drift av nya och liknade avloppssystem/reningsverk, när vi implementerar ny infrastruktur i framtiden.

Printed by Media-Tryck, Lund 2022 NORDIC SWAN ECOLABEL 3041 0903

LUND UNIVERSITY

LUND UNIVERSITY
Faculty of Engineering
Department of Chemical Engineering