TAMPERE UNIVERSITY
OF APPLIED SCIENCES

OPTIMIZATION OF STRUVITE PRODUCTION FROM URINE

Michael Kloet

Bachelor's thesis
May 2016
Degree Programme in Environmental Engineering
Environmental Technology

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Degree Programme in Environmental Engineering
Environmental Technology

Michael Kloet
Optimization of Struvite Production from Urine

Bachelor's thesis 30 pages, appendices 5 pages
May 2016

Artificial fertilisers are essential in modern-day agriculture and food production, providing the necessary nutrients for intensive production and crop growth. Phosphorus is one element that is of special importance in fertilisers as its natural cycle spans over millions of years, essentially making it a finite resource. The majority of phosphorus fertiliser is derived from phosphate rock.

This study researched urine as an alternative phosphorus source for fertiliser purposes through the precipitation of struvite ($MgNH_4PO_4 \cdot 6H_2O$). The main aim of the research was to find the optimal parameters for struvite production, using a series of different variable level combinations. These variables were mixing time and magnesium to phosphorus ratio (Mg:P). The tests were carried out in batches using a pilot struvite reactor at Tampere University of Applied Sciences during April and May 2016.

Results indicated that both longer mixing times and a higher Mg:P ratio have adverse effects on phosphorus removal rates. Phosphorus removal rates varied throughout the experiments, while the amounts of precipitated struvite remained roughly the same. Therefore, the combination that removed the most phosphorus and used the least amount of resources was chosen to be the optimum: 5 minutes of mixing using a Mg:P ratio of 1.1.

Struvite, magnesium ammonium phosphate, phosphorus, urine, nutrient recycling

CONTENTS

1 INTRODUCTION

1.1 Background on phosphorus as fertiliser

Food production globally is heavily dependent on the input of artificial fertilisers. Without these inputs of additional nutrients, such as phosphorus, nitrogen and potassium, non-fertile soils could not be used for agriculture and crop yields would be much lower. (Cordell, D., White, S. 2013)

Running out of resources for producing artificial fertilisers would mean a catastrophe for the global food production, population and economy. Unfortunately, most of the phosphorus that is used for creating fertilisers comes from phosphate rock. This is a resource that only renews over spans of millions of years, and therefore we consider it to be finite. There are increasing concerns around the long-term availability of phosphate rock, with some scientists predicting so-called ‘peak phosphorus’ within the next 30-300 years. This means reaching a peak in phosphorus production, after which it will only decline as all high-quality phosphate rock will have disappeared and costs keep rising to produce similar volumes, up to a point where it is no longer feasible. However, data is not publicly available and there are many complexities and misunderstandings with regards to phosphorus security and peak phosphorus. (Cordell, D., White, S. 2011)

Phosphate rock deposits are unequally distributed over the world, with approximately 95% of remaining reserves located in Morocco, China, the United States, South Africa and Jordan. Morocco controls 85% of remaining reserves, albeit through military occupation of Western Sahara. Many nations are highly dependent on imported phosphorus fertilisers, and this causes geopolitical tensions and risks. China imposed a 135% export tariff on phosphate in order to secure domestic supply, influencing the global market. (Cordell, D., White, S. 2011)

Studies have shown that current practices of phosphorus use in the world are far from optimal, wasting substantial amounts of a finite resource due to inefficiencies. (Schoumans O.F. et al. 2015) According to Cordell et al. (2009), 80% of phosphorus is lost in the entire production chain before it actually reaches the food that we consume. Phosphorus losses to the environment are high, creating significant problems such as eutrophication and natural habitat destruction.

1.2 Struvite

Struvite, magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$), is a white, odourless, inorganic crystalline mineral that forms through precipitation when Mg^{2+}, NH_4^+ and PO_4^{3-} simultaneously occur under favourable conditions.

Struvite can form in wastewater treatment plants, in places where there is an increase in turbulence, such as pumps, aerators and pipe bends. The struvite deposition has negative effects on the efficiency of operations and lifespan of equipment. 5.6 kilometers of piping had to be replaced at the Sacramento Regional Wastewater Plant in California due to struvite fouling. (Doyle, J.D., Parsons S.A. 2002.) Furthermore, accumulated struvite is challenging to remove, since the few effective methods such as jet washing and acid washing are time-consuming, leading to significant downtime in operations. (Stratful, I. et al 2001)

Struvite is also widely known in its form of urinary tract stones or bladder stones in humans and other animals, where it precipitates from urine once the pH is raised high enough due to influences of bacterial infection.

Besides these negative aspects, struvite has useful qualities. Through struvite precipitation, phosphorus can be captured from waste streams and put back into the nutrient cycle. Once such practices are established in larger scale, a country’s dependence on artificial fertilisers based on phosphate rock decreases and a stronger phosphorus and food security can be established.

1.2.1 Precipitation of struvite

The minimum solubility of struvite lies at pH = 9 (Etter, B. 2009). Therefore, pH control is an effective method of preventing or facilitating struvite precipitation. The optimum pH range for struvite precipitation lies between pH 8 – 10. Above pH 10, the solubility rises and struvite is able to re-dissolve. (Sääluoto, K.)

Another essential factor for the precipitation of struvite is the molar ratio between ions. Since one mole of struvite contains one mole of Mg^{2+}, NH_4^+ and PO_4^{3-} each, any of these could be the limiting reagent and stop the process. According to Sääluoto, K., the third factor influencing struvite formation is temperature, with a range of 25 – 90 °C being the optimum.

However, the kinetics behind struvite precipitation are complex and other factors play important roles. Precipitation can be stimulated by adding foreign bodies into the solution. These can act as nucleation seeds that promote crystal formation and growth. (Udert, K.M. et al. 2003) On the other hand, some foreign ions can inhibit crystal growth by blocking potential growing sites or destabilizing the crystal structure (Ibid.).

Pre-treating waste streams at a wastewater treatment plant through forced struvite precipitation could produce a useful product by capturing nutrients. At the same time, the precipitation makes later treatment processes easier and more efficient and reduces the risk of equipment damage and failure. (Stratful, I. et al. 2001)

1.2.2 Struvite as fertiliser

The chemical contents and low solubility of struvite outside the range of pH 8 – 10 make it a good slow-release fertiliser. Compared to conventional fertilisers, the lower solubility causes less leaching of nutrients to runoff waters and therefore less need to reapply fertiliser during a growing season.

Struvite’s main qualities are its high phosphorus content, and the fact that the phosphorus is in a form that is highly bioavailable to plants. Struvite has an approximate NPK value of 6:29:0(Mg)10. Because struvite is phosphorus-heavy, it is ideally used in combination with other fertilisers that provide important nutrients such as nitrogen and potassium.

Overapplication of struvite would increase the soil pH up to a point where it would negatively influence nutrient availability and uptake. (Miso, A., Spuhler, D. 2009)

Studies have shown that the use of struvite in combination with conventional fertilisers can improve overall phosphorus use efficiency, saving resources. Such fertiliser mixes can provide optimal phosphorus uptake throughout a growing season, whereas pure struvite would provide less than optimal phosphorus uptake at the start of a growing season due to its low solubility. (Talboys, P.J. et al. 2015)

1.3 Urine

Urine in itself can be used as fertiliser, since it contains the excess nutrients that the human body could not uptake. However, in a larger scale it is challenging to store and transport significant volumes of it. The unpleasant odour and possible cultural influences might further limit the viability of using urine as a fertiliser. (Miso, A., Spuhler, D. 2009) Legislation may, in some cases, even prohibit the use of urine as a fertiliser for food crops.

Urine is an excellent raw material for the production of struvite. Through the naturally occurring process of ureolysis, or degradation of urea, the pH of stored urine increases (Udert, K.M. et al, 2003). Since pH levels increase above 8, stored urine can be readily used for struvite precipitation without the need of additional chemicals to adjust the pH.

Producing struvite from urine would capture a significant fraction of phosphorus from the urine and condense it in a form that is easier to store, transport and apply as fertiliser. However, nitrogen levels typically remain high in the effluent from the struvite production process, and other important nutrients and micronutrients are not captured by struvite. A positive side to this is that pharmaceuticals and other impurities, such as heavy metals, are also not captured by struvite. (Miso, A., Spuhler, D. 2009)

Utilizing the nutrients from urine would close the nutrient loop that is normally broken when urine is flushed down the drain and eventually ends up, greatly diluted and mixed with other waste, in a wastewater treatment plant. This dilution makes it challenging to extract useful nutrients later, as it requires a lot of energy and other resources.

1.3.1 Urine as a resource in low-income countries

In low-income countries where conventional fertilisers can sometimes be difficult to obtain due to political and other reasons (Etter, B. 2009), producing struvite from urine could be an effective way of creating a valuable product that at the same time can improve farmers' crop yields.

The introduction of urine diverting dry toilets, or UDDT, can improve sanitation and hygiene in communities while also constantly providing them with two valuable resources: human faeces that can be composted and used as soil-improving material, and human urine that can be applied directly as fertiliser or stored and refined into struvite, through a relatively simple and inexpensive process.

Especially in such regions, the benefits of applying fertiliser to crops can be substantial and provide livelihoods to farmers. Introducing the concepts of dry toilets and nutrient recycling is generally easier in low-income countries than it is in developed countries, where infrastructure is already extensively built around and centred on the use of water-based toilets. Preventing the dependence on artificial fertilisers is an effective way of strengthening global phosphorus security.

1.4 Magnesium for struvite production

The addition of magnesium ions to stored urine sets the precipitation of struvite in motion. Therefore, several things are important to keep in mind.

1. The magnesium salt should be well soluble
2. A high magnesium concentration is favoured, to reduce transport and energy costs
3. The price should be competitive to conventional fertilisers
4. The magnesium should come from a sustainable source, preferably as a by-product of another process

In this experiment, magnesium chloride hexahydrate ($Cl_2Mg{\cdot}6H_2O$) was used for its solubility and cost. It is the most widely used precipitant in struvite production (Etter, B. 2009) and is available in different forms for different applications.

Depending on geographical location, waste or by-products of other industries can cost-effectively be used as a source of magnesium. The production of salt from sea water, for example, creates a waste product called bittern, which contains magnesium ions. Studies in Nepal have confirmed that bittern is a viable alternative to the use magnesium salts, with phosphorus removal rates of above 95% (Etter, B. 2009).

Mining waste may contain magnesite rocks, which have magnesium in form of magnesium carbonate. Through special treatment, this can be turned into magnesium oxide and be used as a precipitant in struvite production. (Miso, A., Spuhler, D. 2009.) If no other source of magnesium is locally available, this might be an option in certain regions.

2 SCOPE OF THIS WORK

The aim of this research was to define the influences mixing time and magnesium to phosphorus (Mg:P) ratios have on phosphorus removal rates when struvite is produced out of human urine for fertiliser use. With this data and the experiences of the researcher with the pilot device, the optimal parameters were chosen and suggestions were made for further improvement of the process.

This research was done for the BIOUREA-project of Tampere University of Applied Sciences (TAMK), and was conducted from March to May 2016.

3 MATERIALS AND METHODS

3.1 Struvite reactor

The pilot reactor used in this research was designed by students of TAMK for a study project, and was further developed by TAMK staff. The basic design was derived from the SSWM Toolbox (Miso, A., Spuhler, D. 2009). The reactor was an acrylic cylinder mounted on top of a table, with a tapered bottom to which a hose with tap was attached. The reactor had a lid which held the mixing mechanism in place, a steel crank attached to a rod with blades. A cross-shaped steel pipe with a hole in the centre would be at the bottom of the reactor, locking the mixing mechanism in place.

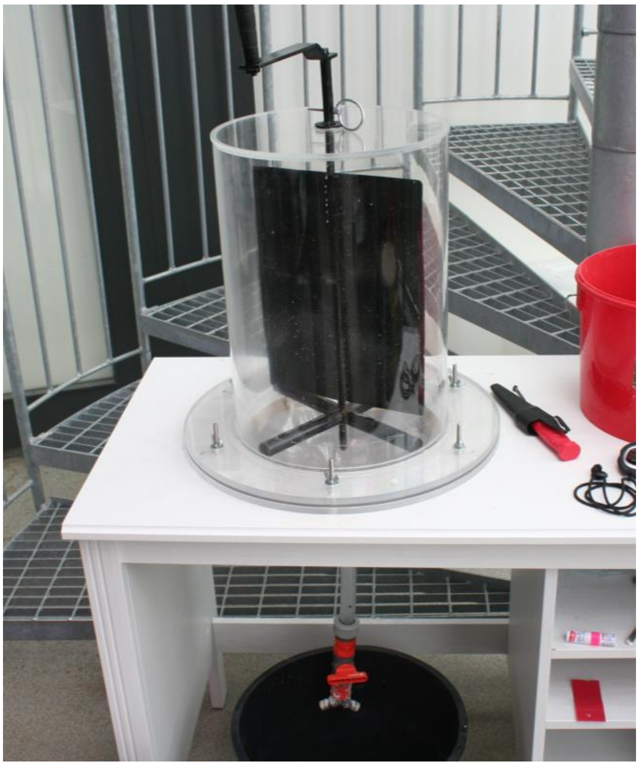


PHOTO 1. Pilot struvite reactor at TAMK

The total volume of the reactor was 30 litres, but for the sake of simplicity urine volumes of roughly 20 litres were used for testing. This would reduce mechanical stress on the system, the risk of overflowing and spillage, and the need to empty the effluent container often.

3.2 Solid-liquid separation

Solid-liquid separation was done by attaching a filter bag to the hose at the bottom of the struvite reactor and using gravity as a driving force. The filter bags were custom made for the experiment, and were made out of Ahlstrom Trinitex ® milk filter media provided by Ahlstrom, a fiber-based materials producer.

Two filter designs were tested: the first design was oval-shaped with one end cut open to allow a snug fit around the hose, the second design was a large rectangular bag with perforations near the opening to accommodate a drawstring. Theoretically, this would make it easier to remove the struvite as opposed to the first design’s narrow opening. After testing, however, significant struvite losses occurred due to leakages. The first, smaller filter bags proved to be more efficient and their size was found to be excellent for the amounts of struvite formed per batch.

PHOTO 2. Left: large bag with holes for drawstring. Right: smaller bag

Several different milk filter fabrics were provided for the experiment. These had their own codenames and densities. The efficiency of the filters was evaluated with test runs, and the most efficient (lowest amount of struvite loss while maintaining acceptable filtration times) material turned out to be K949, 110 g/m^2. Filters bags out of this material were used for the experiments.

PHOTO 3. Uncut sheet of material for the filter bags

3.3 Experiment design

The experiment was conducted as a full factorial experiment. Based on literature, several levels for the two variables, mixing time and Mg:P ratio, were chosen and all possible combinations were tested. Each set of combinations would consist of 2 duplicate tests.

TABLE 1 shows the levels that were chosen for the variables:

TABLE 1. Different levels for the variables

Mixing time (minutes)	**Mg:P ratio**
5	1.1
10	1.5
20	

In addition to this, a screening test was done to see if a mixing time of 60 minutes would be worthwhile to study. This did not show desirable results, and therefore a total of 13 tests were run: 6 in duplicate and the 60 minutes-test only once.

3.3.1 Mg:P ratio

In order to achieve a batch-specific correct Mg:P ratio, the total phosphorus content of the sample first needed to be analysed. This was done by using the Phosphormolybdenum Blue method with Hach Lange LCK349 kits, and analysis through photospectrometry. Analyses were done according to standards ISO 6878-1-1986 and DIN 38405 D11-4. Tests were done in either duplicate or triplicate.

Samples of raw urine and stuvite effluent were diluted 1/500 in order to fall within the measuring range of the LCK349 kits.

3.3.2 Total Nitrogen

Total nitrogen (TN) was studied to get an indication of the average nitrogen content of the stored urine, and to see the efficiency of struvite's nitrogen capture. The results were also vital for another study done in conjunction with this research, which tested different methods in order to capture nitrogen from the struvite process effluents.

Total nitrogen content was measured with Hach Lange LCK138 kits, which utilized Koroleff Digestion (Peroxodisulphate) and Photometric Detection with 2.6-Dimethylphenol in accordance to standard EN ISO 11905-1. Total nitrogen was also measured using the Kjeldahl method with Buchi K-437 wet digestion apparatus and K-314 distiller. Tests were done in either duplicate or triplicate.

For the LCK138 kits, similar 1/500 dilutions were used to be within the measuring range. For Kjeldahl analysis, a smaller dilution of 1/10 was used in order to gain reliable results from titrimetry.

PHOTO 4. Hach Lange kits for TP and TN

3.3.3 Sampling

The urine used in this study originated from summer 2015, when it was gathered from several festivals throughout Finland for the BIOUREA project. It was stored in a 1000-liter tank, which was roughly 80% full at the start of this study (PHOTO 5).

PHOTO 5. Urine tank at the end of the experiments

In order to gain homogenous samples, the tank needed to be mixed before sampling. This was done using a submersible pump and letting it run for at least an hour before taking samples. The exact specifications of the pump can be seen in PHOTO 6 below.

PHOTO 6. FXA Submersible pump, Qmax: 14000 l/h

Since the flow rate of the submersible pump was so high (14000 L/h at 0 meters elevation), it could not be used for obtaining urine samples without significant spillage. Instead, a manual pump was used to fill 20L containers. These containers were then used for each batch. Containers were stored indoors to improve workflow by preventing the need to wait for samples to reach room temperature for analyses.

PHOTO 7. Manual pump used to fill sample containers

PHOTO 8. 20L containers used for sampling and storing effluent

3.4 Procedure

The exact work procedure of the experiments is now described:

1. Urine tank is mixed with submersible pump for at least one hour.
2. 20L containers are filled with urine using a manual pump, each container is marked with its own codename.
3. The containers are brought inside until they reach room temperature
4. When at room temperature, a container is mixed and a sample of roughly 200 mL is taken in a beaker. It is stirred with a magnetic stirrer and pH is measured.
5. 1/500 dilutions are now prepared from the 200 mL sample using volumetric flasks of either 250 mL or 500 mL and an automatic pipette. (1/10 in case of Kjeldahl nitrogen)
6. From these 1/500 raw urine dilutions TP and TN are analysed. In case TN could not be tested that same day, the volumetric flask was stored in a refrigerator.
7. Once TP values are obtained, their average value for each batch is used to calculate how much magnesium chloride is to be added.
8. The corresponding raw urine container is mixed and a volume of 5L is measured four times using a large beaker. The contents are poured into the struvite reactor to reach a final volume of approximately 20L.
9. A dry filter bag is selected, weighed and attached to the bottom of the struvite reactor.
10. The batch-specific amount of magnesium chloride is weighed and added to the raw urine in the struvite reactor.
11. The reactor is manually stirred for the specified amount of time, after which the tap is opened and filtered effluent flows into a large container. In case of leakages, the filter bag is adjusted immediately.
12. Once at least half of the reactor’s contents are emptied, a sample of roughly 200 mL is taken into a beaker from the effluent container.
13. The tap is closed and the effluent container is carefully emptied into a 20L container using a funnel. Any struvite sediment is kept in the bucket at this stage. The effluent container is placed back and the tap is re-opened.
14. The 200 mL effluent sample is taken to a magnetic stirrer and once again pH is measured. From this sample, 1/500 dilutions are made for TP and TN analysis. (1/10 in case of Kjeldahl nitrogen)

15. With the TP results, the phosphorus removal rate is calculated.
16. Meanwhile, filtration continues at the reactor and when necessary, the effluent container is emptied.
17. If the struvite reactor is sufficiently empty of urine, the small amounts of struvite sediment in the effluent container are poured back for filtration. Additionally, the reactor is cleaned with water to loosen any struvite residue near the bottom.
18. Step 17 is repeated until there is no significant turbidity left in the effluent, minimizing struvite filtration losses. If necessary, external pressure to the filter can be exerted to speed up filtration.
19. The filter bag is dried at 50.5 °C until a stable weight has been obtained.
20. The dry filter bag is weighed to determine how much struvite was formed.
21. The dry filter bag is emptied and once again weighed to determine how much struvite could actually be harvested from the filter bag.
22. The struvite is collected in an air-tight container and another batch is tested.

4 RESULTS

Some results with regards to TN could not be obtained due to running out of reagents for the Hach Lange kits. The samples to be analysed were then too diluted to be reliably used with the Kjeldahl mehod and no representative raw material was leftover to create new dilutions.

The complete datalog can be found from the appendix section. In this section, result averages will be used for interpretation.

4.1 Phosphorus removal

Based on raw urine and effluent TP content, phosphorus removal rates were calculated for each batch. The average results of the experiments are displayed in FIGURE 1 below.

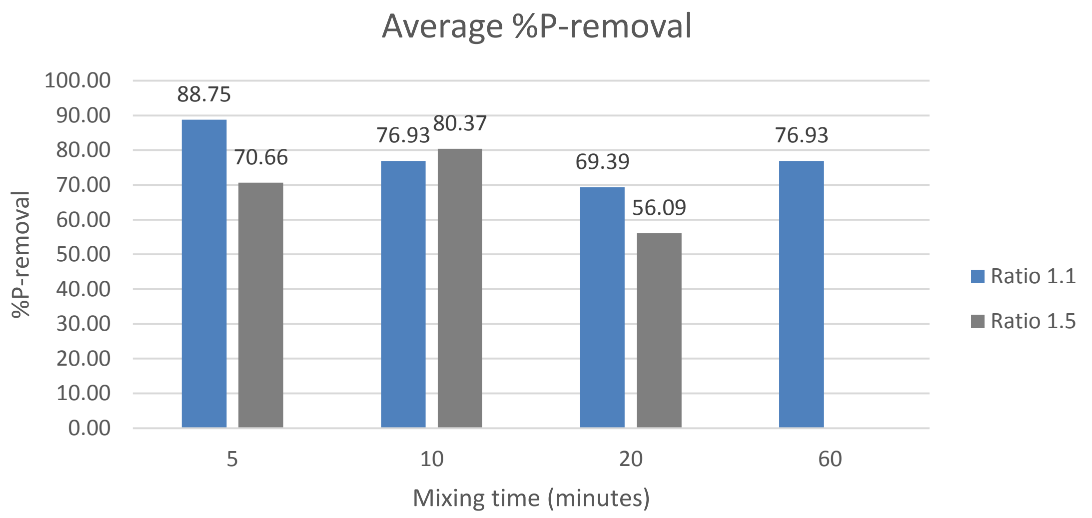


FIGURE 1. Average %P-removal for each test

From the results in FIGURE 1, we can see a negative trend for both ratios as mixing times increase. A 50% excess of magnesium similarly shows a negative effect on phosphorus removal rates when compared to the 10% excess.

The average phosphorus removal for all the 13 experiments conducted was 73.95% with a standard deviation of 15.62%.

4.2 Struvite yield

4.2.1 Filtration

Looking at the average amounts of struvite filtered from the ratio 1.1 batches (FIGURE 2), there appears to be a positive trend as mixing time increases. However, amounts filtered are relatively close to each other, with an average of 26.925g and standard deviation of only 1.694g. These differences can be considered insignificant when considering the mixing times are multiplied 2, 4 and 30 times.

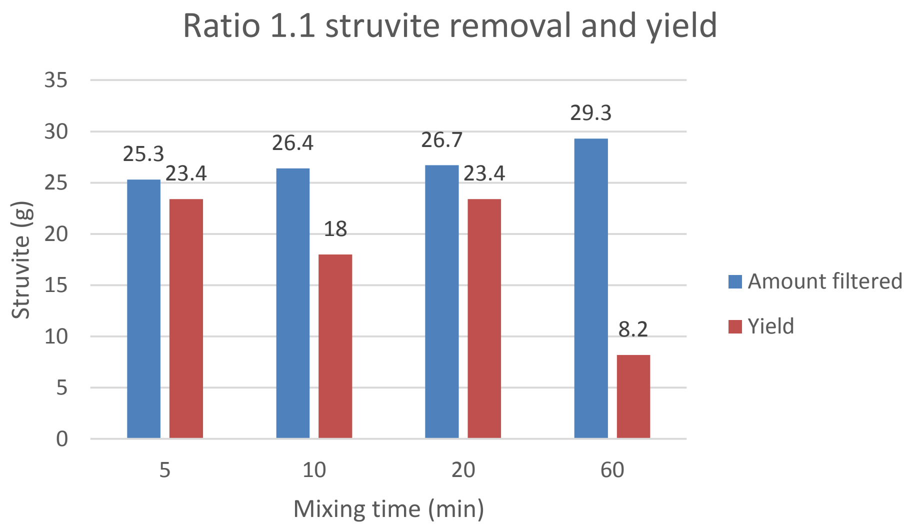


FIGURE 2. Ratio 1.1 struvite removal and yield

In FIGURE 2, the yield specifies the amount of struvite that was successfully harvested from the filter bags. These have a high variation for Ratio 1.1, since these were the first experiments performed and know-how was limited.

With the experience from these first experiments, some practices were developed that minimized losses from this phase. This can clearly be seen from the Ratio 1.5 results in FIGURE 3. Cases where the amounts harvested are higher than the amounts filtered are most likely the results of residual struvite from re-using the filter bags.

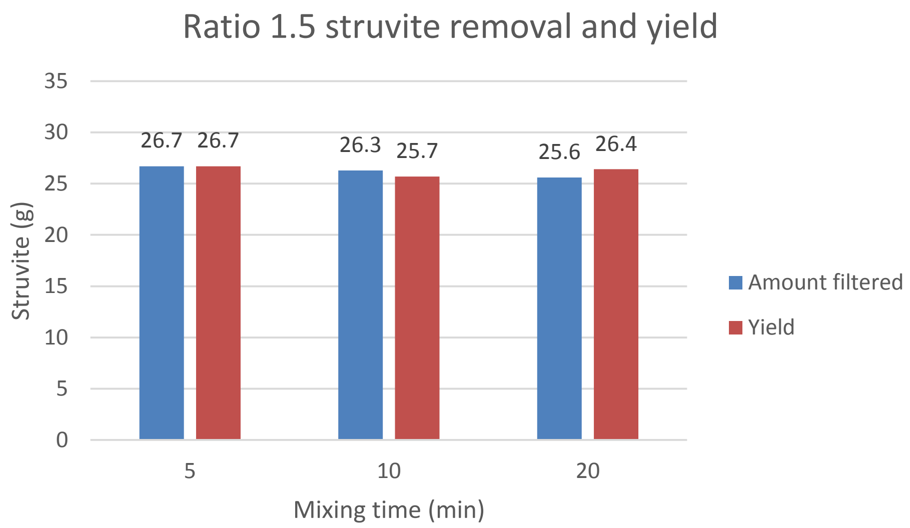


FIGURE 3. Ratio 1.5 struvite removal and yield

For ratio 1.5 the average amount of struvite filtered was 26.2g, with a standard deviation of 0.557g. This average is lower than the average from ratio 1.1.

4.2.2 Theoretical and actual struvite formation

Based on stoichiometry, the amount of phosphorus removed from urine should be proportional to the amount of struvite formed. In all cases, the amount of struvite gathered in the filters did not reach the theoretical maximum yield. This may be due to filtration losses or other factors, such as pH and interference from other ions. The average losses were 33.89% with a standard deviation of 10.90%.

FIGURE 4 displays the average theoretical maximum struvite yield based on each set's measured total phosphorus values. In this case, the actual yield specifies the amount of formed struvite that was captured in the filter. From these values, a loss percentage was calculated.

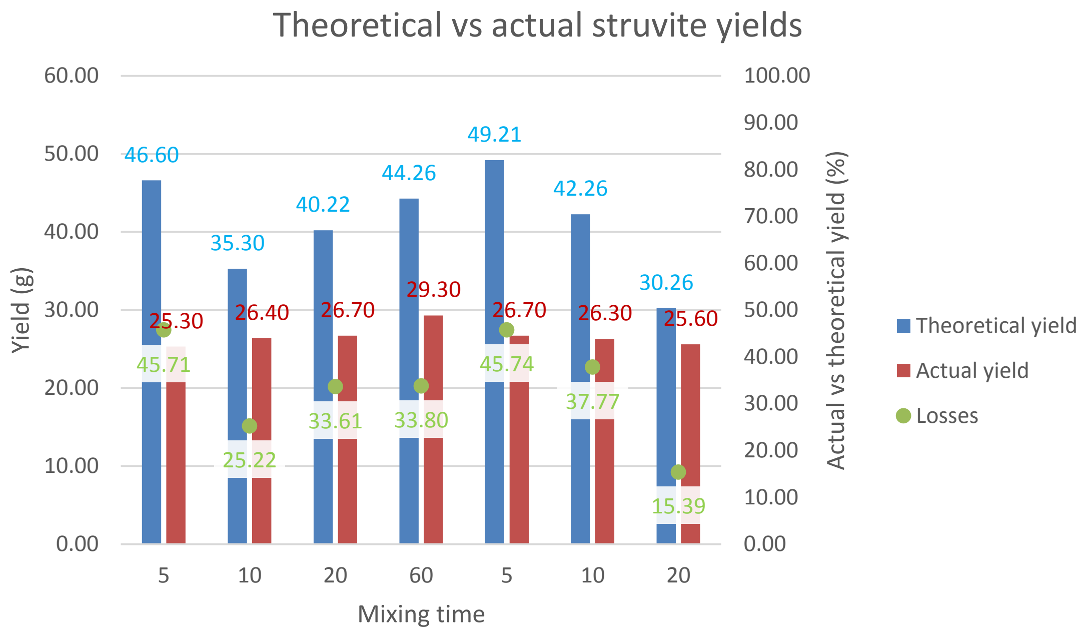


FIGURE 4. Theoretical versus actual struvite yields

Note that losses are lower when the phosphorus removal rates are lower, because this also affects the theoretical maximum yield.

5 DISCUSSION

The results of the study provide answers to the research questions while at the same time creating new ones. Increases in mixing time and Mg:P ratio have shown to affect negatively on phosphorus removal rates from urine. At the same time, amounts of struvite produced have been relatively similar across all the experiments.

5.1 Theoretical maximum yield

Comparing the amounts of struvite formed with theoretical maximum yields leads to the question: ‘Where does the phosphorus that isn’t precipitated as struvite go?’ Filtration losses are one explanation, as the smallest crystals of struvite could pass through the filter, and a slight turbidity could sometimes be detected with the naked eye when pouring the effluent away.

Another important thing to note is that total phosphorus was measured as an indicator in this study. It is possible that some of the phosphorus in urine is in a different form than phosphate, and therefore unavailable for direct struvite precipitation. However, this would mainly limit the amount of phosphorus that can be removed from urine and does not explain why the amounts of struvite precipitated fall within a narrow range and do not reach their maximum potential yields.

Since the work procedure contains many steps, it is likely that some error originates from there. Automatic pipettes could be inaccurate and this error would transfer to the dilutions and results. The HACH spectrophotometer that was used for TP and TN analyses might not have been calibrated recently enough, causing more inaccuracies.

5.2 Nutrient recovery

Disregarding the losses, we can come to the conclusion that 5 minutes of mixing at Mg:P ratio 1.1 is the most resource-efficient combination out of all the factor level combinations tested. This research showed that this maximizes phosphorus removal while still producing similar amounts of struvite compared to the other level combinations. From all chosen values, this uses the least amount of time and magnesium chloride.

Nitrogen levels in the effluent are still high, with averages around 2.9 g/L (APPENDIX 2 and 3). There is potential here for further nutrient recovery. Concentrations of other nutrients such as potassium and calcium were not tested in this study and could provide valuable insights to further potential.

5.3 Methodological improvements

This research was the first study done at TAMK with the pilot struvite reactor. The researcher noticed several things that could improve workflow and productivity of the system and process.

5.3.1 Mixing

First of all, the mixing mechanism of the reactor was sometimes difficult to use. The vertical rod had to slide into a locking mechanism at the bottom of the reactor in order to turn properly without damaging the system. Finding this hole that would lock it into place was not easy when the reactor was filled with 20 litres of urine and sometimes caused delays of several minutes before mixing could start properly.

Automating the mixing would be the next step in developing the struvite reactor. Some sort of electrical mixer could be used to keep the mixing time and speed constant if struvite production in a larger scale is desired.

5.3.2 Filtration

The filter bags used in the experiment provided some challenges. Attaching them to the hose at the bottom of the tank was done with zip ties to ensure a snug fit. In reality, many leakages occurred and the zip ties had to be loosened and re-attached several times before filtration could properly be done. This filter bag attachment method could be changed and improved to make it less laborious.

While the filters fulfilled their function in this experiment, it is unknown whether or not their shape and size was optimal. If struvite production were to be done in a larger scale, the optimal shape, surface area and material of the filter bags should be studied more deeply in order to maintain a constant quality.

One important thing that the researcher noted during this experiment was the importance of drying the struvite. If left untouched during the drying process, struvite will tend to form large clumps and stick to the filter bag material, making it difficult to harvest without contaminations. Breaking it into smaller pieces was often required to get anything out of the bag. If periodical agitation is performed during the drying process, struvite will form smaller clumps that do not stick to the filter bag material and can be poured out of the bag straight away. This arguably also speeds up the drying process. An example is shown in PHOTO 9.

PHOTO 9. Agitated struvite (left) and untouched struvite (right)

5.3.3 Magnesium source

While the magnesium chloride that was used in this experiment was effective, it is not necessarily the most efficient source of magnesium for precipitation. Finding a local Finnish magnesium source would at least reduce the carbon footprint of the product. It is possible that the Finnish mining industry creates by-products or waste that contain magnesium. While magnesite rock does require special pre-treatment before it can be used as precipitant, a study could be done to see if there is a viable application in struvite production for this by- or waste product.

6 CONCLUSIONS

The study was successfully carried out and the main research goals were fulfilled. As a conclusion, both longer mixing times and a higher Mg:P ratio have adverse effects on phosphorus removal in the struvite production process. Amounts of struvite formed were fairly similar throughout the experiment, though phosphorus removal rates varied. Therefore, phosphorus removal rate was chosen as an indicator for the efficacy of the process. This study concludes that the optimal mixing time is 5 minutes, and the optimal Mg:P ratio is 1.1. The experiences of the researcher may prove valuable to future studies and several suggestions have been made for the improvement of the reactor and production process.

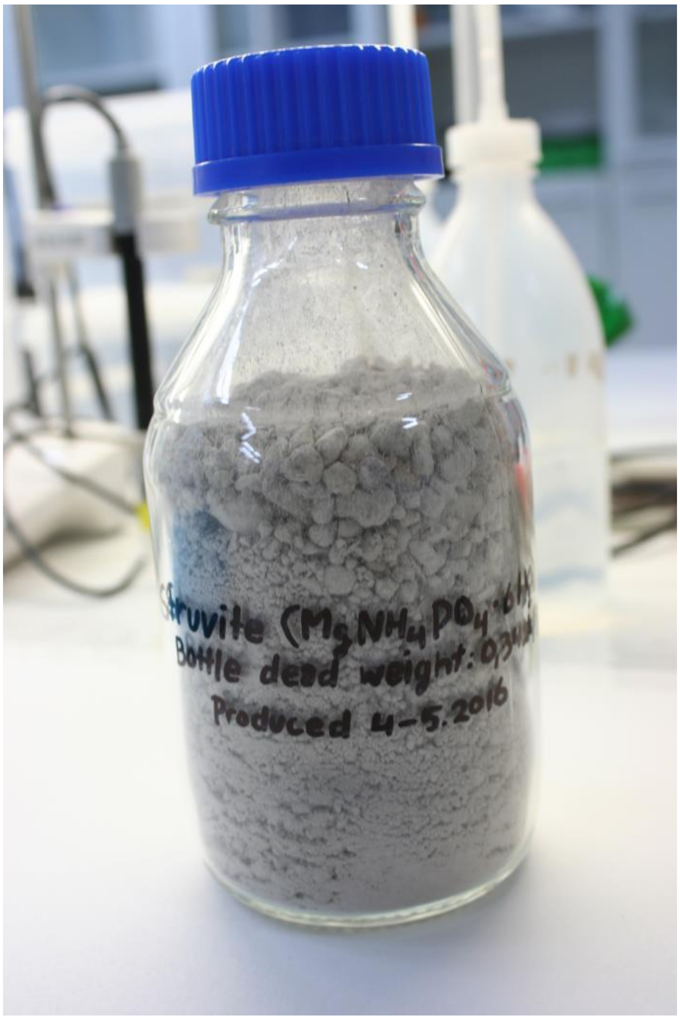


PHOTO 10. Struvite formed during this study, approximately 300 grams

REFERENCES

Cordell, D., Drangert, J.-O., White, S. 2009. The story of phosphorus: Global food security and food for thought. Glob. Environ. Change 2009, 19, pg. 292-305.

Cordell, D., White, S. 2011. Peak Phosphorus: Clarifying the Key Issues of a Vigorous Debate about Long-Term Phosphorus Security. Sustainability 2011, 3(10), pg. 2027-2049

Cordell, D., White, S. 2013. Sustainable Phosphorus Measures: Strategies and Technologies for Achieving Phosphorus Security. Agronomy 2013, 3, pg. 86-116.

Doyle, J.D., Parsons S.A. 2002. Struvite formation, control and recovery. Water Research. Volume 36. Pages 3925-3940.

Etter, B. 2009. Process optimization of low-cost struvite recovery. Master's thesis.

Etter, B., Udert, K.M., Gounden, T. 2015. VUNA Final Report. Eawag. Dübendorf, Switzerland.

Liu, X. 2013. Influence of process parameters on phosphorus recovery by struvite formation from urine. Water Science & Technology. Volume 68, no. 11. Pages 2434-2440.

Miso, A., Spuhler, D. 2009. Fertiliser from urine (Struvite). SSWM www.sswm.info. Date accessed: 9.5.2016. http://www.sswm.info/category/implementation-tools/reuse-and-recharge/hardware/reuse-urine-and-faeces-agriculture/fertili

Schoumans O.F. et al. 2015. Phosphorus management in Europe in a changing world. AMBIO 2015, 44(Suppl. 2). Pg. 180–S192

Stratful, I. 2001. Conditions influencing the precipitation of magnesium ammonium phosphate. Water Research. Volume 35, no. 17. Pages 4191-4199.

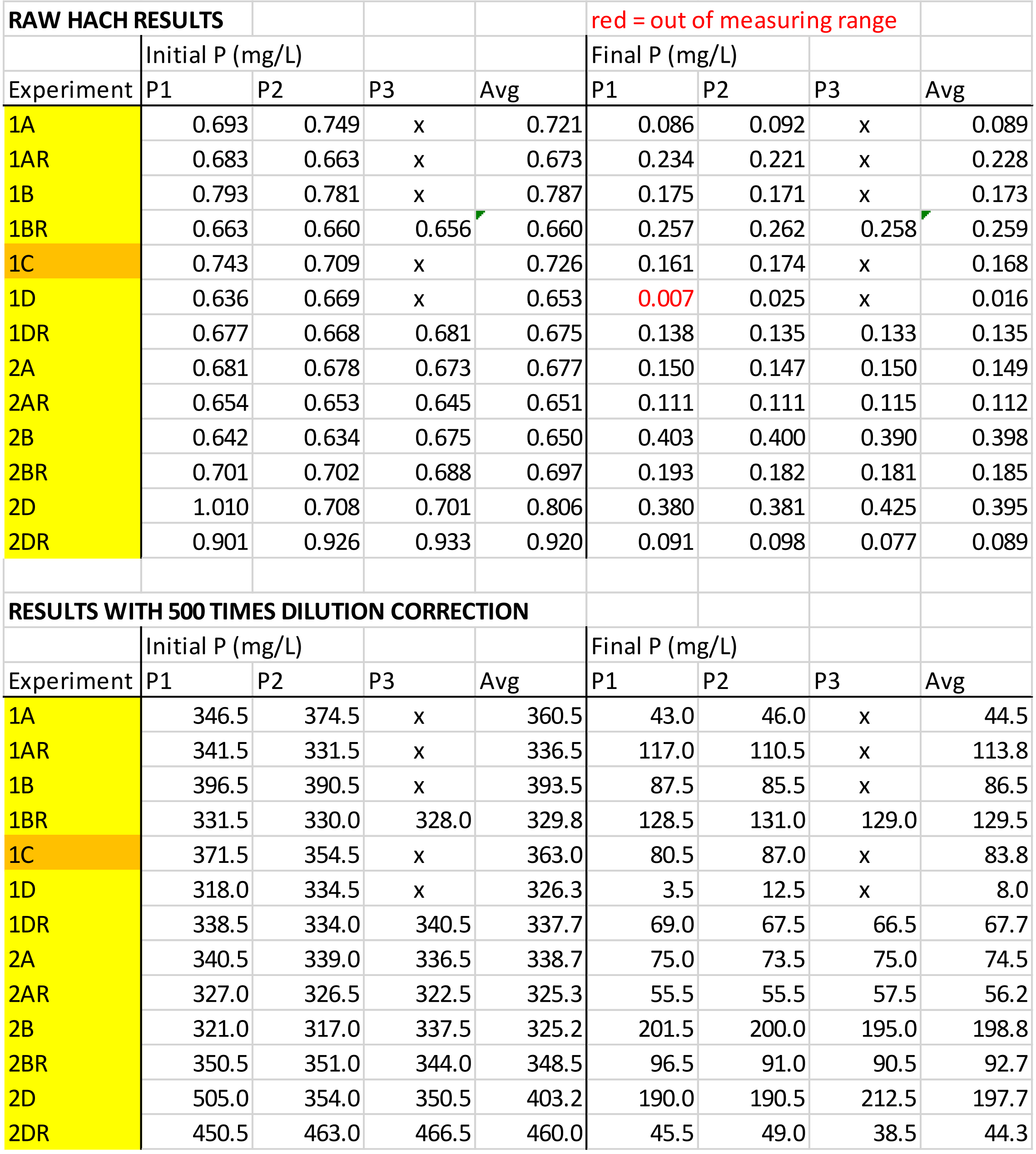
Sääluoto, K. Year unknown. Struviitin valmistus.

Talboys, P.J. et al. 2015. Struvite: a slow-release fertiliser for sustainable phosphorus management? Plant Soil (2016) 401 pg. 109–123

Udert, K.M. et al. 2003. Urea hydrolysis and precipitation dynamics in a urine-collecting system. Water Research. Volume 37. Pages 2571-2582

APPENDICES

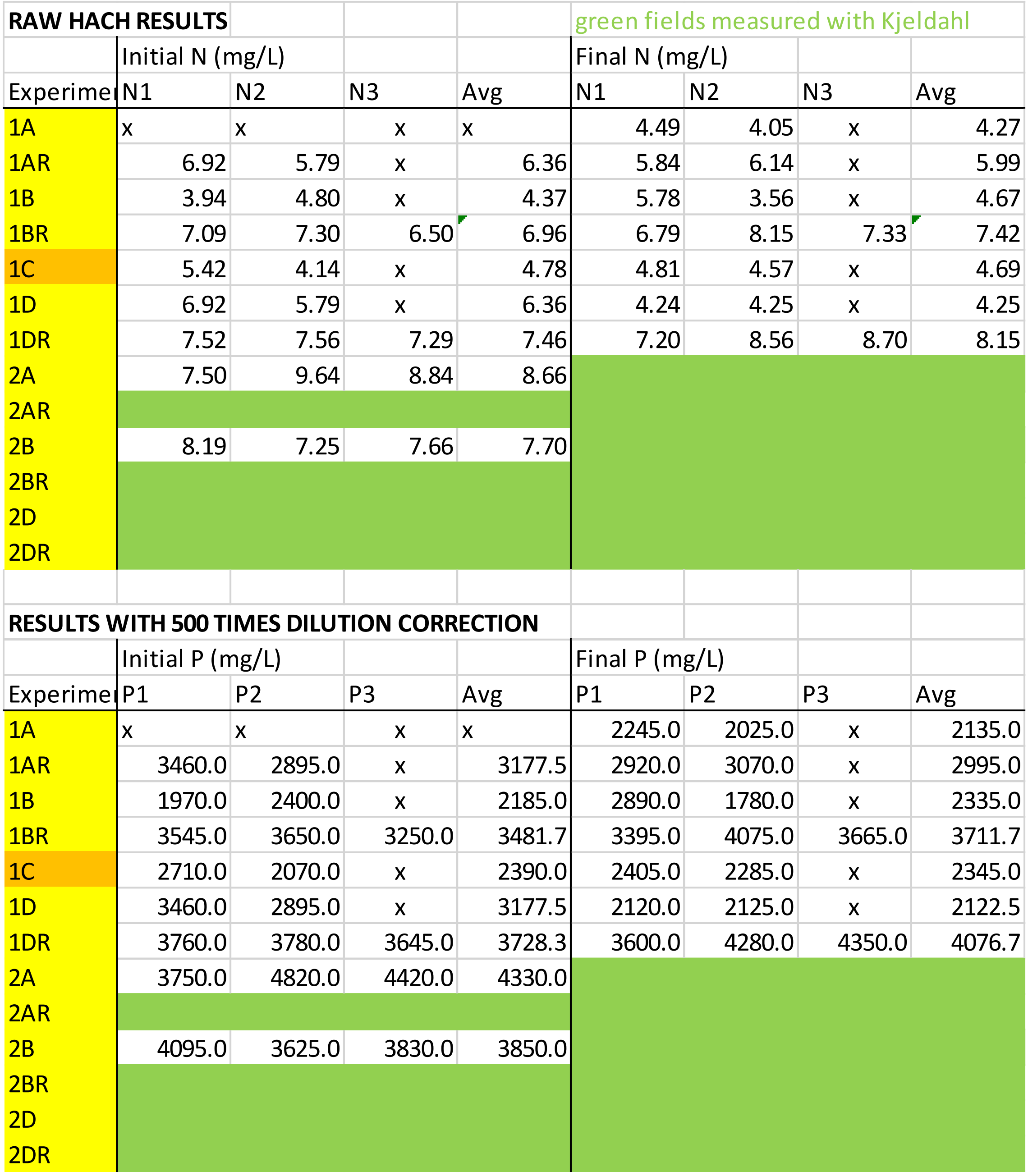
Appendix 1. Results from total phosphorus analyses with HACH



RAW HACH RESULTS					red = out of measuring range			
	Initial P (mg/L)				Final P (mg/L)			
Experiment	P1	P2	P3	Avg	P1	P2	P3	Avg
1A	0.693	0.749	x	0.721	0.086	0.092	x	0.089
1AR	0.683	0.663	x	0.673	0.234	0.221	x	0.228
1B	0.793	0.781	x	0.787	0.175	0.171	x	0.173
1BR	0.663	0.660	0.656	0.660	0.257	0.262	0.258	0.259
1C	0.743	0.709	x	0.726	0.161	0.174	x	0.168
1D	0.636	0.669	x	0.653	0.007	0.025	x	0.016
1DR	0.677	0.668	0.681	0.675	0.138	0.135	0.133	0.135
2A	0.681	0.678	0.673	0.677	0.150	0.147	0.150	0.149
2AR	0.654	0.653	0.645	0.651	0.111	0.111	0.115	0.112
2B	0.642	0.634	0.675	0.650	0.403	0.400	0.390	0.398
2BR	0.701	0.702	0.688	0.697	0.193	0.182	0.181	0.185
2D	1.010	0.708	0.701	0.806	0.380	0.381	0.425	0.395
2DR	0.901	0.926	0.933	0.920	0.091	0.098	0.077	0.089

RESULTS WITH 500 TIMES DILUTION CORRECTION								
	Initial P (mg/L)				Final P (mg/L)			
Experiment	P1	P2	P3	Avg	P1	P2	P3	Avg
1A	346.5	374.5	x	360.5	43.0	46.0	x	44.5
1AR	341.5	331.5	x	336.5	117.0	110.5	x	113.8
1B	396.5	390.5	x	393.5	87.5	85.5	x	86.5
1BR	331.5	330.0	328.0	329.8	128.5	131.0	129.0	129.5
1C	371.5	354.5	x	363.0	80.5	87.0	x	83.8
1D	318.0	334.5	x	326.3	3.5	12.5	x	8.0
1DR	338.5	334.0	340.5	337.7	69.0	67.5	66.5	67.7
2A	340.5	339.0	336.5	338.7	75.0	73.5	75.0	74.5
2AR	327.0	326.5	322.5	325.3	55.5	55.5	57.5	56.2
2B	321.0	317.0	337.5	325.2	201.5	200.0	195.0	198.8
2BR	350.5	351.0	344.0	348.5	96.5	91.0	90.5	92.7
2D	505.0	354.0	350.5	403.2	190.0	190.5	212.5	197.7
2DR	450.5	463.0	466.5	460.0	45.5	49.0	38.5	44.3

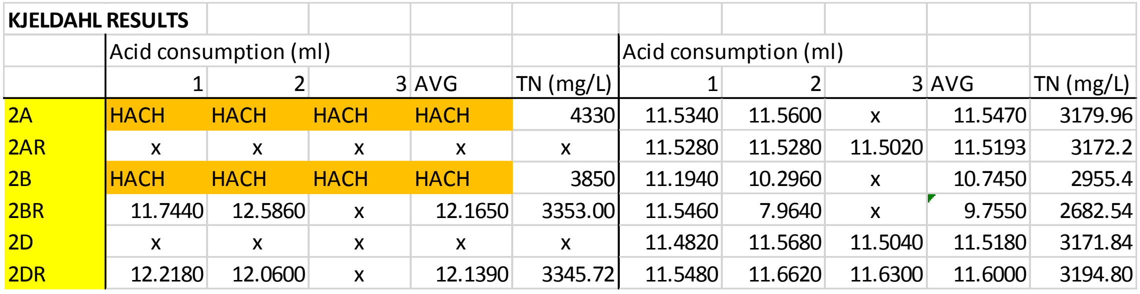
Appendix 2. Results from total nitrogen analyses with HACH



RAW HACH RESULTS					green fields measured with Kjeldahl			
	Initial N (mg/L)				Final N (mg/L)			
Experime	N1	N2	N3	Avg	N1	N2	N3	Avg
1A	x	x	x	x	4.49	4.05	x	4.27
1AR	6.92	5.79	x	6.36	5.84	6.14	x	5.99
1B	3.94	4.80	x	4.37	5.78	3.56	x	4.67
1BR	7.09	7.30	6.50	6.96	6.79	8.15	7.33	7.42
1C	5.42	4.14	x	4.78	4.81	4.57	x	4.69
1D	6.92	5.79	x	6.36	4.24	4.25	x	4.25
1DR	7.52	7.56	7.29	7.46	7.20	8.56	8.70	8.15
2A	7.50	9.64	8.84	8.66	🟩	🟩	🟩	🟩
2AR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2B	8.19	7.25	7.66	7.70	🟩	🟩	🟩	🟩
2BR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2D	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2DR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

RESULTS WITH 500 TIMES DILUTION CORRECTION								
	Initial P (mg/L)				Final P (mg/L)			
Experime	P1	P2	P3	Avg	P1	P2	P3	Avg
1A	x	x	x	x	2245.0	2025.0	x	2135.0
1AR	3460.0	2895.0	x	3177.5	2920.0	3070.0	x	2995.0
1B	1970.0	2400.0	x	2185.0	2890.0	1780.0	x	2335.0
1BR	3545.0	3650.0	3250.0	3481.7	3395.0	4075.0	3665.0	3711.7
1C	2710.0	2070.0	x	2390.0	2405.0	2285.0	x	2345.0
1D	3460.0	2895.0	x	3177.5	2120.0	2125.0	x	2122.5
1DR	3760.0	3780.0	3645.0	3728.3	3600.0	4280.0	4350.0	4076.7
2A	3750.0	4820.0	4420.0	4330.0	🟩	🟩	🟩	🟩
2AR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2B	4095.0	3625.0	3830.0	3850.0	🟩	🟩	🟩	🟩
2BR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2D	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2DR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Appendix 3. Results from total nitrogen analyses through Kjeldahl Method



KJELDAHL RESULTS										
	Acid consumption (ml)					Acid consumption (ml)				
	1	2	3	AVG	TN (mg/L)	1	2	3	AVG	TN (mg/L)
2A	HACH	HACH	HACH	HACH	4330	11.5340	11.5600	x	11.5470	3179.96
2AR	x	x	x	x	x	11.5280	11.5280	11.5020	11.5193	3172.2
2B	HACH	HACH	HACH	HACH	3850	11.1940	10.2960	x	10.7450	2955.4
2BR	11.7440	12.5860	x	12.1650	3353.00	11.5460	7.9640	x	9.7550	2682.54
2D	x	x	x	x	x	11.4820	11.5680	11.5040	11.5180	3171.84
2DR	12.2180	12.0600	x	12.1390	3345.72	11.5480	11.6620	11.6300	11.6000	3194.80

Appendix 4. Experiment details, theoretical vs actual struvite yield

Filter used	Date executed	Experiment Code	Mixing time	Mg:P ratio	Mg to add/L (g)	Mg to add total (g)	Mg added total (g)		P init (mg/L)	P final (Mg/L)	%P removal	P removed from batch(mg)	P (mmol)	Theoretical struvite yield(g)	Actual struvite filtered (g)	Actual vs theoretical yield (%)
120s	13.4.2016	1A	10	1.1	1.7226	34.452	34.5472		360.5	44.5	87.66	6320	204.0685	50.1		
110-2	19.4.2016	1AR	10	1.1	1.60861	32.1722	32.251		336.5	113.75	66.20	4455	143.8489	35.3	26.4	74.78
110s	14.4.2016	1B	20	1.1	1.8809	37.61816	37.6759		393.5	86.5	78.02	6140	198.2564	48.7	26.8	55.08
110	20.4.2016	1BR	20	1.1	1.57753	31.551	31.6128		330	129.5	60.76	4010	129.4801	31.8	26.6	83.71
120l/110s	15.4.2016	1C	60	1.1	1.734	34.6879	34.706		363	83.75	76.93	5585	180.3358	44.3	29.3	66.20
110	18.4.2016	1D	5	1.1	1.55888	31.178	31.2084		326.25	8	97.55	6365	205.5215	50.4	25	49.57
110-2	21.4.2016	1DR	5	1.1	1.61306	32.3212	32.6292		337.5	67.65	79.96	5397	174.2654	42.8	25.6	59.86
110	25.4.2016	2A	10	1.5	2.20566	44.1132	44.3517		338.5	74.5	77.99	5280	170.4876	41.8	22.4	53.54
110-2	28.4.2016	2AR	10	1.5	2.12092	42.418	42.4532		325.5	56.15	82.75	5387	173.9425	42.7	30.2	70.74
110-2	26.4.2016	2B	20	1.5	2.11687	42.3374	42.4214		325	199	38.77	2520	81.36907	20.0	22.4	112.17
110	2.5.2016	2BR	20	1.5	2.27023	45.4046	45.4864		348.5	92.665	73.41	5116.7	165.2147	40.5	28.8	71.03
110	27.4.2016	2D	5	1.5	2.62607	52.5214	55.5796		403	197.65	50.96	4107	132.6122	32.5	23.6	72.51
110-2	2.5.2016	2DR	5	1.5	2.99732	59.9464	59.9838		460	44.35	90.36	8313	268.4211	65.9	29.8	45.24

Appendix 5. Experiment details, pH and filter efficiency

Filter used	Date executed	Experiment Code	pH init	pH final	Struvite filtered (g)	Harvested yield (g)	%Efficiency
120s	13.4.2016	1A	8.76	8.78			
110-2	19.4.2016	1AR	8.94	8.83	26.4	18	68.2
110s	14.4.2016	1B	8.99	8.89	26.8	20	74.6
110	20.4.2016	1BR	8.90	8.84	26.6	26.8	100.8
120l/110s	15.4.2016	1C	9.00	8.83	29.3	8.2	28.0
110	18.4.2016	1D	8.89	8.91	25	23.2	92.8
110-2	21.4.2016	1DR	8.90	8.82	25.6	23.6	92.2
110	25.4.2016	2A	8.92	8.76	22.4	20.2	90.2
110-2	28.4.2016	2AR	8.93	8.85	30.2	31.2	103.3
110-2	26.4.2016	2B	8.94	8.8	22.4	24	107.1
110	2.5.2016	2BR	8.96	8.79	28.8	28.8	100.0
110	27.4.2016	2D	8.91	8.87	23.6	24.6	104.2
110-2	2.5.2016	2DR	8.97	8.78	29.8	28.8	96.6