AMMONIA REMOVAL AND RECOVERY USING HEATED STRUVITE AS AN ADSORBENT

by

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Abstract

The removal and recovery of aqueous ammonia from BNR plant centrate or supernatant is an important research area. Stringent ammonia discharge requirements must be met to avoid fish toxicity in the receiving waters. Completely removing ammonia from the process reduces the load recycled back to the head of the plant and minimizes operational problems associated with high return loads. The controlled recovery of phosphate and ammonia into struvite with a dedicated fluidized bed crystallizer has led to the production of commercially valuable struvite pellets for the fertilizer industry. However, excess ammonia remains after struvite crystallization.

The purpose of this research was to initiate the development of a nitrogen removal technology. This was achieved using the isothermal decomposition of struvite to remove ammonia. The decomposed pellets were subsequently placed into an ammonium solution for removal of excess aqueous ammonium. Struvite was shown to decompose into a mixture of magnesium phosphates and struvite. Satisfactory decomposition was achieved with a minimum of 100°C for 30 minutes. Ammonium removal reached up to 99% for a solution pH 8. Effective ammonia-N removal required a minimum reaction duration of between 15-30 minutes with a 66.7g/L dose.

Struvite heated at higher temperatures worked as a better substrate to remove aqueous ammonia-N. Molar ratio comparisons show that the ammonia removed from solution is likely incorporated into newly formed fine struvite, rather than being incorporated into the heated struvite. This provides evidence in favour of a dissolution-reformation

mechanism, whereby heated struvite acts a source of magnesium and phosphate. Heated struvite is more soluble than unheated struvite, because water of hydration and ammonia are removed from the pellet. Mass balances were reasonable but were complicated by natural adsorption of atmospheric water onto heated pellets.

The economic viability of this technology may be unfavourable. A trade off exists between high ammonium removal and dissolution of pellets, which are worth up to $3000 per tonne in the United States. The total daily cost to remove nitrogen using this technology is estimated to be about 15 times greater than using side stream nitrification.

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1 Introduction

The primary sources of nitrogen in waste are feces, urine, and food-processing plants, with the majority existing as free ammonia, and the remainder is incorporated in organic material (Viessman & Hammer, 2004). At environmentally relevant pH values, unionized ammonia is acutely toxic to fish species, and therefore is cause for concern. An excess of nutrients in a water body has also been shown to cause eutrophication and eventual death of the aquatic ecosystem (Schindler, 1974). This has resulted in ammonia removal from waste streams becoming a key political priority in many jurisdictions around the world.

Ammonia can be removed by primary treatment and secondary biological treatment in which the activated sludge contains about 6% nitrogen by mass (Viessman & Hammer, 2004). After digestion, the nitrogen content is reduced to approximately 4%. Anaerobic sludge digestion has been found to release much of the nitrogen and phosphorus contained in the biosolids, back into the waste stream in concentrations much higher than in the influent (Britton et al., 2005). Unfortunately, if magnesium is present in the influent, the solution may become supersaturated with respect to magnesium ammonium phosphate, commonly known either as MAP or struvite, and spontaneous crystallization in digester pumps and pipes is likely to occur (Fattah et al., 2008). Hydraulic capacity becomes compromised and pumping and maintenance costs increase, since acid must be flushed through the pipes to dissolve and remove the encrustation. Plants also risk non-compliance with nutrient discharge limits.

Controlled production of struvite can be advantageous for any biological nutrient removal (BNR) plant and easily fits into existing solids processing facilities. By harvesting struvite, hydraulic capacity is maintained and maintenance costs are reduced.
As the phosphate content in biosolids is decreased, sludge volume may also be reduced by up to 30% or 49% compared to EBNR and chemical phosphorus precipitation, respectively, which minimizes final disposal costs (Woods et al., 1999). Also, phosphorus and nitrogen loads on the plant are reduced, which diminishes the amount of chemical polishing required, as well as aeration (Britton et al., 2007).

Pilot studies at five treatment plants have shown exceptional removal and recovery of phosphorus (Table 1). Phosphorus and nitrogen concentration can be reduced by up to 95 and 20 percent, respectively. Maximum reduction in phosphorus and nitrogen loading on any plant was 30 and 10 percent, respectively. Additional cost savings on acid flushing can be significant. For example, the Gold Bar Treatment Plant saved $100,000 per year after implementing a pilot project.

A life cycle analysis of wastewater-derived struvite fertilizer production at the 68.7 mgd, Gold Bar WWTP, found that approximately 12,000 tonnes of carbon dioxide emissions per year can be offset versus conventional fertilizer production, largely due to the mining, thermal processes and long transport distances required by the latter (Britton et al., 2007). The struvite pellets produced are a highly pure, slow-release fertilizer suitable for sale in the $1B per year container nursery market (Baur, 2009). In Japan, the market price was $375 USD per tonne after three years' experience of operating and selling recovered

struvite from a full scale plant (Ueno & Fujii, 2001). In North America, the market price is still under flux but has reached as high as $3000 USD per tonne (Mavinic, 2010). Thus, nutrient recovery benefits both the environment and the process integrity, while providing a significant revenue stream for the treatment plant owners.

Table 1 Struvite benefit comparison case studies.

Treatment Plant	Flow	Influent P	Influent N	P removal	N removal	P load reduction	N load reduction	Struvite Prod.	Yearly Rev.
	mgd	(mg/L)	(mg/L)	(%)	(%)	(%)	(%)	(t/yr)	($ mill)
Gold Bar	68.7	207	805	75	20	20	5	1200	3.6
Nansemond	18.3	140-700	500-800	80	42	30	10	1650	4.9
Durham	20	600	1200	95	19	24	6	430	1.3
Penticton	5.6	37-71	197-436	91	10	N/A	N/A	N/A	N/A
Lulu Island	21.1	39-88	410-907	90	4	N/A	N/A	N/A	N/A

Pilot and full scale studies have been shown to completely remove and recover phosphorus from the feed streams. However, nitrogen concentrations are usually in large excess and can still result in harm to the receiving waters. Typically, remaining ammonia is removed by recycling the effluent back into the biological process for conventional nitrification-denitrification (Turker & Celen, 2007). Other methods include side stream nitrification, breakpoint chlorination, ion-exchange, electrodialysis, evaporation, and reverse osmosis (Stefanowicz et al., 1992), as well as physical adsorption onto activated carbon and zeolite materials (Fumoto et al., 2009). These technologies are limited in use to particular pH conditions and initial influent concentrations and high temperatures. Furthermore, at concentrations near 1000 mg/L and volumes near 70 m^3, the capital and operating costs become too high (Stefanowicz et al., 1992). A sustainable approach,

based on nitrogen recovery, is ideal to stabilize the overall nitrogen balance and to potentially reduce the overall economics cost of the wastewater treatment plant (Turker & Celen, 2007).

To overcome the disadvantages of the aforementioned nitrogen removal technologies, it was hypothesized that struvite pellets can be heated to thermally decompose struvite, removing ammonia and water from the crystal. Decomposed pellets can then act as an aqueous ammonium removal agent, restoring the crystal back to its original chemical form. This recycling process can theoretically continue until the excess ammonia is completely removed.

In this research, a synthetic feed solution, with concentrations similar to effluent from Lulu Island Waste Water Treatment Plant (LIWWTP), was used to simulate the effectiveness at relevant and realistic concentrations (Table 2). It is believed that amorphous newberyite can be recycled back into the MAP crystallizer to reform crystalline struvite (Equation 1).

$MgHPO_4$ (s) + NH_3 (aq) + $6H_20$ → $MgNH_4PO_4 \bullet 6H_20$ (s) (Equation 1)

Table 2 Struvite crystallizer effluent characteristics.

	2009		2010	
Component	Concentration	Molar ratio	Concentration	Molar ratio
N	300 mg/L	N:P = 65:1	700 mg/L	N:P = 150:1
P	10 mg/L	Mg:P = 37:1	10 mg/L	Mg:P = 37:1
Mg	30 mg/L	N:Mg = 4.2:1	30 mg/L	N:Mg = 4.2:1

2 Research objectives

The purpose of this research was to initiate the development of a nitrogen removal technology. This was to be achieved through the thermal decomposition of struvite and subsequent placement of the decomposition product into an ammonia-rich solution, at concentrations that are typical of UBC/Lulu Island pilot struvite crystallizer effluent.

The decomposition reaction is dependent on the temperature, atmospheric conditions, heating duration, oven size and type, and the sample size. A key objective was to gain a better understanding of struvite decomposition variables and the reaction mechanism so that struvite decomposition could be optimized.

To fully develop a nitrogen recovery technology, an understanding of the conditions necessary to uptake ammonia is required. Another key objective was to determine optimal pH conditions, reaction durations, reactant mass, and heating temperatures, in order to maximize ammonia uptake into heated struvite pellet, while minimizing the competing production of fine struvite.

The final objective was to provide an initial understanding of the economic viability of the process compared to sidestream nitrification.

3 Literature review

A review of struvite chemistry in terms of thermal stability is presented This is followed by a review of analytical detection techniques and aqueous ammonia removal methods.

3.1 Solution equilibria

Pure ammonia in solution exists as two species: unionized ammonia (NH_3) and ammonium ion (NH_4^+). The relative proportion of these two species is dependent on the pH of the solution. Phosphate in solution exists as four species: phosphoric acid (H_3PO_4), dihydrogen phosphate ($H_2PO_4^-$), hydrogen phosphate (HPO_4^{2-}), and orthophosphate (PO_4^{3-}). The relative proportion of these four species is also dependent on the pH of the solution. Magnesium exists in solution in the cationic form with a hexahydrate shell ($Mg^{2+}\bullet 6H_2O$). However, at basic pH values, magnesium cation can become bound to the hydroxyl ion in various ways.

3.2 Struvite chemistry

The mineral magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4\bullet 6H_2O$) is known commonly as struvite. A pure crystal contains equimolar amounts of magnesium, ammonium and orthophosphate, along with six waters of hydration. Depending on solution pH, the formation of struvite can occur through two competing reactions (Equation 2-3).

$Mg^{2+} + NH_4^+ + HPO_4^{2-} + OH^- + 5H_2O \rightarrow MgNH_4PO_4\bullet 6H_20$ (Equation 2)

$Mg^{2+} + NH_4^+ + H_2PO4^- + 2OH^- + 4H_2O \rightarrow MgNH_4PO_4\bullet 6H_20$ (Equation 3)

3.3 Struvite (MAP) process

In 1999, BC Hydro provided funding for the University of British Columbia to initiate research into nutrient recovery from wastewater. BC Hydro was interested in technologies that could lead to discoveries of new sources of fertilizers for use in nutrient deprived lakes and rivers. The UBC teams' solution was to channel anaerobic digester centrate or supernatant to a dedicated sidestream fluidized bed reactor for controlled crystallization of struvite. The process shown in Figure 1 involves centrate or supernatant influent entering the injection port and mixing with a magnesium source and a caustic source, to precipitate struvite out of solution. The fluidized bed reactor maintains a constant and sufficient upflow velocity to allow for crystal growth and agglomeration into a large pellet that can be harvested when desired. The success in the removal of phosphorus from the wastewater has allowed this process to be commercialized and several full scale plants now operate throughout the world. However, the process performs poorly in removing ammonia from solution, when an excess of ammonia exists in the centrate or supernatant.

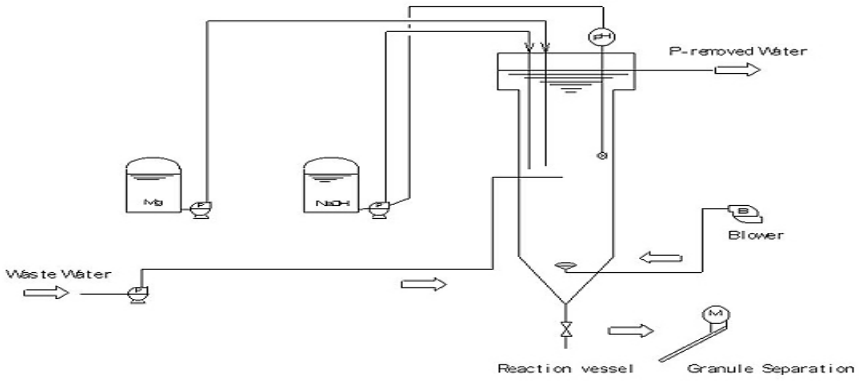

Figure 1 Struvite process diagram.

3.4 Ammonia as an energy source

The recovery of ammonia from wastewater benefits the treatment plant, but also can be viewed as a source of energy (Christensen et al., 2005; Klerke et al., 2008). Gaseous ammonia can be trapped in an acidified solution of sodium borohydride ($NaBH_4$) via Equation 4.

$NH_4^+ + BH_4^- \rightarrow NH_4BH_4$ (Equation 4)

Ammonium borohydride, provides storage of hydrogen on both the ammonium cation and the borohydride anion. This solid compound also contains the highest gravimetric hydrogen density at approximately 24%. It has been found that 20 wt% of hydrogen is released at temperatures lower than 160°C (Karkamkar et al., 2009). Thus, the release of ammonia from heated struvite, and subsequent storage in borohydride, may play a role in the hydrogen economy.

Alternately, gaseous ammonia can be trapped in magnesium chloride, forming magnesium hexammine chloride $Mg(NH_3)_6Cl_2$ (Jacobsen et al., 2007; Christensen et al., 2006). This compound can be thermally decomposed to magnesium chloride and recycled back to the struvite crystallizer, to remove remaining ammonium ions from solution.

3.5 Struvite thermal decomposition

It is important to understand the thermal stability and phase transitions of struvite and related compounds in order to more effectively produce pure agriculturally desired

fertilizer products (Bhuiyan et al., 2008). This knowledge is also useful in developing an ammonium recovery technology using recycled, thermally decomposed struvite. It has been proposed by many researchers that heating struvite results in the expulsion of the six waters of hydration and the chemically bound ammonia (Equation 5), forming magnesium hydrogen phosphate, commonly known as newberyite (Sugiyama et al., 2005; Frost et al., 2004; Wang et al., 2006).

$MgNH_4PO_4 \bullet 6H_20\,(s) + heat \rightarrow MgHPO_4\,(s) + NH_3\,(g)\uparrow + 6H_20\,(g)\uparrow$ (Equation 5)

3.5.1 Thermal mass loss

The calculated mass loss is used to qualitatively determine the average composition of struvite after heating. The theoretical mass loss for struvite based on Equation 5 is 51.42% (44.08% water, and 7.34% ammonia). It was found that, between 100-140 °C, the mass lost was stable at approximately 45% for any duration two hours or longer, indicating that increasing the time for heating does not significantly increase the mass lost (Frost et al., 2004; Wang et al., 2006).

3.5.2 Thermal gravimetric analysis (TGA)

Struvite decomposition is dependent on the local atmospheric conditions (ie. nitrogen atmosphere versus moist atmosphere) (Frost et al., 2004). Using a TGA, it was found that struvite originating in human kidneys or urinary tracts, or guano formations, decomposed at 85°C when heated at a rate of 2°C/min. The reaction product was not identified. Sarkar (1991) however, found that struvite decomposed at approximately 106°C, when heated at a rate of 5°C/min. Wang et al. (2006) found that struvite decomposed between 100-

140°C, although the heating rate was not stated. All three groups found only one peak in the differential TGA curve, suggesting that water and ammonia are simultaneously released.

When the heating rate was decreased to 1°C/min, Frost et al. (2004) found that the decomposition occurred at three distinct temperatures: 39.5, 57.8, and 82.6°C. Struvite decomposition is highly dependent on heating rate. This results in a contradictory hypothesis in which ammonia is first released, followed by the waters of crystallization. The waters of crystallization are hypothesized to be strongly hydrogen bonded to the magnesium cation because a strong infrared OH stretching band is observed on samples of heated struvite (Cahil et al., 2007). The crystallographic data shows that the water molecules in struvite form donor hydrogen bonds, which are of the shortest length for all known minerals.

(Bhuiyan et al. 2008) studied the thermal decomposition of struvite in dry air and observed a conversion to amorphous newberyite. The decomposition of struvite was highly dependent on the rate of heating, with slower rates of heating achieving maximum rate of decomposition at lower temperatures.

3.5.3 Thermo-gas (TG) titrimetry

Non-isothermal analytical methods, such as TGA, do not reflect the real nature of transformation because the thermal analytical curves are characteristic of heat and gas transport processes, rather than the intrinsic transformation process (Paulik, 1999). Heat transfer is the slowest process and thus controls the rate of mass loss (Paulik & Paulik,

1975). They determined the composition and course of the elementary partial struvite decomposition reactions, as well as how the elementary partial reactions are influenced by experimental conditions by using simultaneous thermo-gas titrimetry (TG) and evolved gas analysis (EGA). Quasi-isothermal and quasi-isobaric conditions, and were used to detect the changes in the different gaseous decomposition products evolved. The technique operates as follows: The temperature inside the furnace heats up at a fast rate until the sample begins to decompose and lose mass. This sends an electrical signal to the furnace shutting it off until the rate of mass change decreases at which point the furnace heats up again. This essentially provides for the quasi-isothermal decomposition conditions such that the thermal analytical curve is not erroneously dictated by heat-transfer. The evolved gas is trapped in water. A potential difference develops between the pH electrodes, which induces an automatic burette to titrate the ammonia-water solution with hydrochloric acid. The strength of this method is the overlapping decomposition reactions are separated in space and time. It was found that five moles of crystallization water leave the crystal first followed by one mole of crystallization water. The third step involves simultaneous release of ammonia and the water of constitution. It was interesting to note that approximately 5% of ammonia was calculated to leave the struvite crystal at the onset of heating. The mechanism proposed shows the final product as magnesium pyrophosphate (Equation 6-8), rather than amorphous newberyite.

$MgNH_4PO_4 \bullet 6H_20 \rightarrow MgNH_4PO_4 \bullet H_20 + 5H_20$ (Equation 6)

$MgNH_4PO_4 \bullet H_20 \rightarrow MgNH_4PO_4 + H_20$ (Equation 7)

$2MgNH_4PO_4 \rightarrow Mg_2P_2O_7 + 2NH_3 + H_2O$ (Equation 8)

Paulik (1999) also found that struvite decomposition depends on water vapour pressure. At a high vapour pressure, the hypothesized mechanism does not require the middle elementary reaction (Equation 7) and instead proceeds via Equations 9-10.

$MgNH_4PO_4 \bullet 6H_2O = MgNH_4PO_4 \bullet H_2O + 5H_2Of$ (Equation 9)

$2MgNH_4PO_4 \bullet H_2O = Mg_2P_2O_7 + 3H_2O + 2NH_3$ (Equation 10)

At a lower water vapour partial pressure, the decomposition was found to take place in one step (Equation 11).

$2MgNH_4PO_4 \bullet 6H_2O = Mg_2P_2O_7 + 13H_2O + 2NH_3$ (Equation 11)

3.5.4 Evolved gas analysis (EGA)

Evolved gas analysis (EGA) and combined differential thermal analysis mass spectrometry (DTA/MS) can be used to determine the type and amount of gaseous reaction products during heating of minerals. Muller-Vonmoos et al. (1977) used a thermoanalyzer, combined with a quadrupole mass spectrometer, to perform simultaneous DTA, TGA and evolved gas analysis. During heating, weight loss occurs and the evolved gases are instantly quantitatively detected by the mass spectrometer. The location of evolved gas peaks has been shown to be dependent on the degree of saturation of the bulk material (Yariv et al., 1989). This effect may interfere with the analysis of heated struvite and struvite after an uptake experiment, in which water may be adhered to the pellets. Koel et al. (1997) found that it is more appropriate to analyze the evolved gases using thermogravimetry/gas chromatography (TG/GC) and designed an instrument

by connecting a low volume furnace to a gas chromatograph interfaced by a computer controlled pneumatic sampler. The spectrum produced is called a thermochromatograph because evolved gases can be resolved into components according to two independent variables, namely, temperature and time. There are two main drawbacks to this method. The instrument is not very sensitive when the evolved gases make up only a small proportion of the total mass. This was not a problem with the heating of struvite, which theoretically loses 51.42% mass. Also, the monitoring is "pseudocontinuous" as the evolved gases take time to go through the GC and, thus, mixing can occur. Overlapping decomposition processes were separated using factor analysis and principle component analysis (PCA). Koel et al. (1998) successfully separated and detected the evolved gases from an ammonium salt finding that 73.7% of water evolved between 90-190°C, and 23.1% water evolved simultaneously with 100% of ammonia between 240-320°C. The remaining 3.2% of water evolved between 450-570°C.

3.5.5 Inductively coupled plasma (ICP) spectroscopy

Two ICP methods were developed for nitrogen determination in fertilizers, although they have never been tested on struvite. Nham (1993) developed an ICP-AES method for direct nitrogen determination in fertilizer. This removes the time consuming digestion period, which is usually required in colorimetry analysis. Jaber et al. (2009) improved the technique by removing matrix interferences by incorporating a hydride generator system (ICP-AES-HG). This technique reduced the problems with background nitrogen levels in the air and in solution that plagued the first method. The mean values of N, using both methods, matched well with the standard colorimetric method.

3.5.6 Fourier transform infrared spectroscopy (FT-IR)

Banks et al. (1975) used FT-IR measurements to track the composition of the solid phase during the aqueous conversion process of struvite to newberyite. The characteristic band of absorbance for struvite is at 1442 cm^{-1} ($_{v4}$ NH_4^+ bending mode). Babic-Ivancic et al. (2006) used this result in conjunction with IR spectra for newberyite (peaks at 1237, 1171, and 890 cm^{-1}), to present a semi-quantitative estimate of the ratio of newberyite to struvite in a solid mixture using FT-IR. Well-defined mixtures of struvite and newberyite were prepared and a calibration curve was constructed by plotting the absorbance of the struvite bands versus the proportion by mass of struvite in the sample. This method may be useful for determining percent struvite versus percent newberyite composition after heating, assuming that the thermal conversion is in fact struvite to newberyite. This method may also be useful for determining the success of ammonium removal into pellets.

3.5.7 Ammonium content using distillation and titration

The ammonia remaining in the solid was analyzed by distillation and titration in HCl solution (Stefanowicz et al., 1992). Ammonia was observed to be released even at low temperatures (Table 3). The identity of the roast product was stated as $Mg_3(PO_4)_2$ rather than amorphous newberyite. However, the researchers did not analyze the roast product to determine its chemical identity.

Table 3 Content of NH_4^+ in magnesium phosphate sediment after drying or roasting in various temperatures for 24 hours.

Heating temperature (°C)	Content of $NH4^+$ (%)
50	2.7
100	1.2

Heating temperature (°C)	Content of $NH4^+$ (%)
150	0.4
250	0

3.5.8 ^{31}P Magic angle spinning nuclear magnetic resonance (^{31}P MAS NMR)

Sugiyama et al. (2005) heated struvite samples for 3 hours and found (using XRD) that, between 100 and 150°C, the hexahydrate was converted to monohydrate. Between 200 and 500 °C, an essentially amorphous XRD pattern was observed. Structural information of amorphous phases cannot be determined using XRD, necessitating the use of solid state ^{31}P MAS NMR. Using this technique, it was shown that the amorphous compounds between 200 and 500 °C correspond to $MgHPO_4$. Above 800°C, XRD has been shown to convert to $Mg_2P_2O_7$ (Paulik, 1999). This result suggests that $Mg_3(PO_4)_2$ is not formed as suggested by (Stefanowicz et al., 1992).

3.5.9 Heating in acid and alkali solutions

He et al. (2007) heated struvite in an alkali solution (NH_4^+:OH^- 1:1) for 2 hr at 90°C, forming $MgNaPO_4$. Upon re-introduction into an ammonium solution, the Na^+ ion substituted for NH_4^+, because Na^+ is a less stable univalent cation than NH_4^+. Results show that, after 6 reuse cycles, ammonium removal was maintained at 84%.

Alternately, Zhang et al. (2004) found that MAP powder can release ammonium to form $MgHPO_4$ at pH < 5.0 and heating temperatures greater than 40°C. The resulting decomposition residues effectively removed ammonium from solution. However, this method allowed about 4% of phosphate and magnesium loss. The molar ratio of N:P

increased dramatically with the increase of temperature from 25°C to 40°C, indicating that ammonium was selectively released from MAP under a relatively high temperature. So, a high temperature was not only preferable for ammonium release, but also for keeping phosphate in the residual precipitations.

3.6 Aqueous recovery of ammonium

Sarkar (1991) found that struvite is thermally unstable in air at temperatures above 50°C and loses part or all of its ammonia and water molecules, depending on the time and temperature of heat treatment. Ultimately, magnesium hydrogen phosphate was suggested to form from the decomposition of dittmarite, which is thermodynamically more stable than struvite. Upon room-temperature rehydration, struvite was reformed along with unknown hydrates and newberyite, depending on the amount of ammonia left in the structure.

3.6.1 Struvite and newberyite solubility

The solubility products of newberyite and struvite are shown in Equation 12 and Equation 13, respectively (Ohlinger et al., 1999; Taylor et al., 1963). The magnitude of newberyite solubility is much greater than struvite solubility. Heated struvite is likely to be more soluble than newberyite as both ammonia and crystalline water are no longer holding the crystal together. Effectively, heated struvite acts as a source of magnesium and phosphate ions.

Ksp(newberyite) = 1.58E-6 → Pksp (newberyite) = 5.80 (Equation 12)

Ksp (struvite) = 5.37E-14 → pKsp (struvite) = 13.27 (Equation 13)

3.6.2 Solution-mediated reformation mechanism

Babic-Ivancic et al. (2006) argue that a solution-mediated conversion process is the most plausible transformation mechanism for struvite to newberyite. A precipitation diagram was constructed which showed the approximate concentration regions where struvite, newberyite, and their mixtures exist at room temperature. The ratio of initial supersaturation ratios of struvite to newberyite ($S_{struvite}/S_{newberyite}$) had a strong influence on the struvite to newberyite conversion. Boistelle et al. (1983) previously found that struvite always crystallizes first when $S_{newberyite}/S_{struvite}$ has a value less than 2. It was also found that for $S_{newberyite}/S_{struvite}$ greater than 4, newberyite crystallized first, and for ratios between 2 to 4, the first phase to crystallize was dependent on the initial pH value. It was further found that newberyite is formed and most stable at excess Mg concentrations and low pH values. This presents a trade off; Newberyite is preferentially formed in solution at pH values of approximately 6.58, and the preformed struvite pellets dissolve into the solution.

3.6.3 Dissolution reformation mechanism

Sugiyama et al. (2005) argue in favour of a similar mechanism known as dissolution-precipitation. They found that ammonium was better removed at pH 8 rather than pH 10, because newberyite is more soluble at lower pH. The solubilized ions are hypothesized to react with aqueous ammonium, forming struvite. It was shown that, by allowing the pH to drop from 8 to 6 during uptake, ammonium removal of up to 93% can be achieved. Finally, Sugiyama et al. (2009) found that increasing the mass of newberyite placed in the reactor caused an increase in the ammonium removal. This may because a larger mass of struvite acts as a bigger source of magnesium and phosphate ions.

3.6.4 Complete acid dissolution reformation mechanism

Stefanowicz et al. (1992) introduced heated struvite into ammonia water (1000 mg/L) and lowered the pH to a value of 1-2. The solid was completely dissolved, releasing aqueous magnesium and phosphate into solution. Caustic solution was added to increase the pH back to a value 9-10, causing the reformation of MAP, and the lowering of ammonia concentrations to below 1mg/L. The best conditions were when the reaction time was five hours or more. The specific ammonia removal rate was approximately 71.4 mg N/ g roast product.

3.6.5 Gaseous adsorption

Activated carbon and zeolite adsorbents have been used to recover ammonia gas (Fumoto et al., 2009). These adsorbents are not ideal because of the high temperatures needed to desorb ammonia. Evolved gaseous ammonia and water were measured using quadrupole mass spectrometry with m/z 15 and 18, respectively. Heated MAP exhibited hysteresis and thus was shown to contain pores. Bigger pores were observed at 105°C compared to 300°C. Gaseous ammonia was best absorbed at lower temperatures.

4 Materials and methods

The basic experimental design and research methodology is presented. Heating, drying, aqueous uptake, and analysis are outlined.

4.1 Reactor design

The bench-scale reactor was rectangular with inside dimensions 11.5cm X 11.5cm X 20.5cm as shown in Figure 2. A rectangular impeller with dimensions 10cm X 4cm X 0.3cm stirred the reactor contents and was powered by a Dayton® DC gear motor (1/30 hp, 90V, 0.42A). A pH probe (Oakton® WD-35801-00 epoxy body) was mounted inside the reactor in order to monitor the pH continuously. The pH probe used was calibrated with three pH standards (pH 4, 7, and 10). The pH probe was interfaced to a Fischer Scientific Accumet® pH meter 50, which read the pH values electronically. The probe was calibrated before each experiment. A conductivity meter (Oakton® TDS/Conductivity/°C metre Conio Series) measured the temperature and conductivity of the feed solution. A separate hole was drilled into the top of the reactor to allow for caustic addition with a 1ml syringe. Two batches of caustic were made (1M and 6M) in order to increase the pH quickly or more slowly in the reactor, respectively.

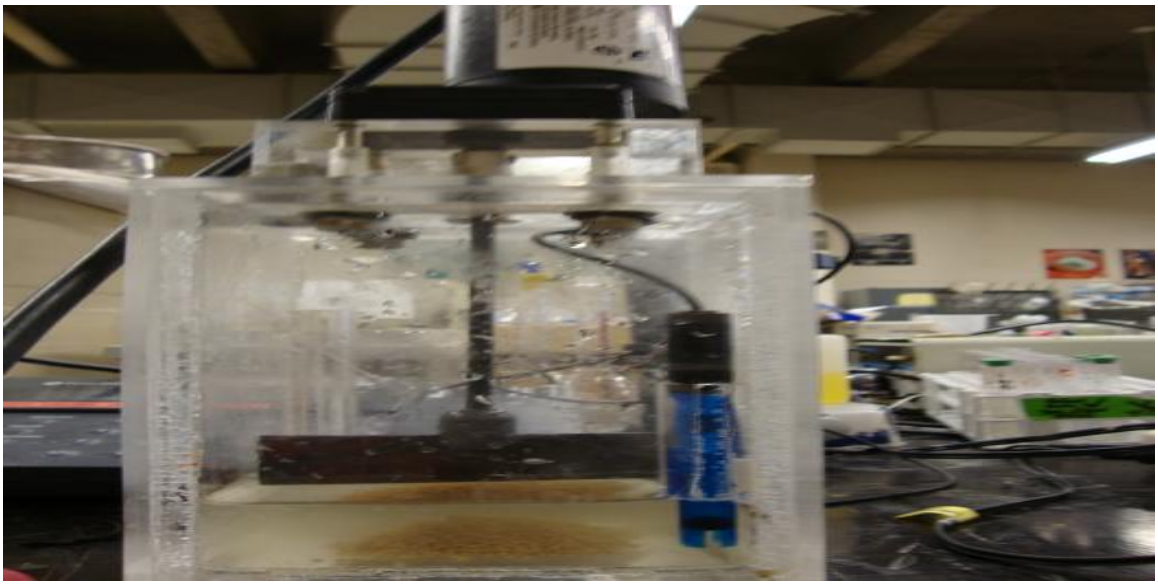

Figure 2 Struvite uptake reactor with feed and heated struvite batch.

4.2 Thermally decomposing struvite

Struvite was selected from a large batch obtained from the Gold Bar WWTP and sieved through a No. 8 (2.36mm) and retained on a No. 10 (2.0mm). Thus, all struvite pellets for heating were between the size range of 2.0mm-2.36mm. Two different ovens were used throughout the duration of the experiments, because the first oven broke. The oven used in the Part 1: 2009 experiments was a Fisher Isotemp 2.5 cubic foot forced air model, and the oven used in the Part 2: 2010 experiments was a Lab Line L-C model. Struvite was heated isothermally at temperatures ranging from 40 to 200°C, for durations ranging from 30 minutes to 24 hours. After heating, struvite was either placed on the lab bench to cool to room temperature, and to achieve stable mass, or was placed in the vacuum desicator to achieve stable mass.

4.3 Feed solution characteristics

The feed solution was made with the following ingredients:

Magnesium chloride hexahydrate, $MgCl_2 \bullet 6H_2O$ (CAS 7791-18-6)

Sodium dihydrogen phosphate, Na_2HPO_4 (CAS 7558-79-4)

Ammonium chloride, NH_4Cl (CAS 12125-02-9)

DI water: 18.6 μS/cm

The feed solution for Part 1 and Part 2 are shown in Table 4.

Table 4 Feed solution makeup for 2009 and 2010.

Species	Part 1: 2009	Part 2: 2010
Mg	30	30
N	300	700
P	10	10
pH	6.63-7.08	6.65-6.76

4.4 Aqueous uptake experiments

Feed solution was added to the reactor using a 1L graduated cylinder in 2009 and with a 500 ml volumetric flask in 2010 with quantities of 750ml and 500ml, respectively. The initial pH of the solution was measured. The temperature and conductivity of the feed solution was also measured. A 5ml aliquot of the feed solution was drawn directly from the reactor using a 5ml volumetric pipette. The contents were emptied into a small test tube and two drops of H_2SO_4 were placed into the test tube to reduce to pH<2 for sample preservation. The pH in the reactor was then increased using 6M NaOH for rapid increase, and 1M NaOH for precisely achieving the appropriate pH value defined. For the 2009 experiments, once the pH setpoint was reached, a 30 ml syringe was used to take an aliquot of solution at the pH setpoint and the contents were filtered (Whatman® cellulose nitrate membrane filters 0.45μm 25mm diameter) into a 5ml test tube and preserved with two drops of H_2SO_4. A similar procedure was conducted for the 2010 experiments except that a 5ml volumetric pipette was used to accurately obtain the aliquot. Also, if any crystallized struvite was found attached to the paper, it would be placed back into the

reactor so that the crystals would re-enter the solution. A 5ml aliquot of the adjusted feed was drawn from the beaker and placed in a test tube and preserved with two drops of H_2SO_4. This sample served as the baseline for the initial mass of magnesium, nitrogen, and phosphorus. An aluminum dish was tared on a balance and the appropriate mass of heated struvite was placed into the dish. The moment this struvite was placed into the reactor, was assigned as the start time of the uptake experiment. Every 15 minutes, for a duration of two hours, a 5ml sample was taken from the reactor using the respective procedures (ie. 2009, and 2010), so that a time series of the reaction progress could later be plotted. During the uptake experiment, the pH would decline as struvite was being formed. The pH was maintained by dropping 1M NaOH through the top of the reactor using a 1ml syringe. At the end of the 2 hour period, the solution was vacuum filtered through a 10 cm ceramic Buchner funnel using a filter paper with 50μm pore size (Whatman® 50 Hardened 9cm diameter). The filtrate was used to wash the retained pellets and reactor surfaces twice in order to remove any fine struvite that may be adsorbed to the surfaces. The pellets were then transferred to a stacked series of three sieves and a pan with mesh decreasing in diameter. The sieves had mesh diameter 1mm, 500μm, and 250μm (No. 18, 35, 60), respectively. The filtrate was used to wash the reactor surfaces one more time before the final filtration. The fine struvite were retained on the filter paper and dried.

4.5 Pellet drying and collecting

The pellets and fine struvite were dried at room temperature for a minimum of 24 hours on the stacked series of sieves (No.18, No.35, and No.60) and filter paper, respectively.

The sieves were shaken so that any small crystals were separated and retained on the appropriate sieve. The mass of struvite remaining on each sieve and the pan was taken, and then each component was stored in a sample bag (Nasco Whirl-pak®). The fine struvite retained on the filter paper was scraped off the filter paper and into an aluminum weigh dish using an aluminum spatula. Some samples were stored in a LABCONCO vacuum desicator at 17mm Hg, while others were stored on the lab bench. This was because the vacuum desicator was found not sufficient to prevent water from reabsorbing to the surface of the pellets and fines.

4.6 Struvite product sample preparation

Three different types of struvite were analyzed: struvite pellets that had gone through a heating procedure only, struvite pellets that had gone through a heating procedure and an uptake procedure, and struvite fines which carried through the heating and uptake procedure or were newly formed during the uptake period. The samples were finely crushed using a ceramic mortar and pestle; approximately 40 mg or 200mg were placed in a 250ml volumetric flask during 2009 and 2010 experiments, respectively. One pipette full (approximately 30 drops) of concentrated HCl (CAS No: 7647-01-0) was placed into the flask to reduce to pH 2, and then was DI water (18.6 μS/cm) was added to make up the volume. The flask was shaken by hand and was allowed to digest the struvite sample for a minimum of 24 hours or until all solid material was dissolved and no longer visible. The contents were then transferred to a centrifuge tube for storage.

4.7 Aqueous analytical methods

Analytical methods for detection of magnesium, ammonia-N, and orthophosphate are outlined here. The instrument operational parameter details are provided in Appendix A.

4.7.1 Magnesium

Samples were diluted appropriately with DI water. Nitric acid was used for preservation and lanthanum nitrate was used as an internal standard. The prepared sample was mixed using a vortex (Scientific Industries Vortex-Genie 2). Magnesium analysis was done using flame atomic absorption spectrophotometry with a Varian Inc. SpectraAA 200 Fast Sequential Atomic Absorption Spectrophotometer and a Varian SPS5 Sample Preparation System. A five point calibration curve was constructed.

4.7.2 Ammonia-N

Samples were diluted appropriately using DI water. The samples were analyzed using flow injection analysis with a Lachat Instruments QuikChem 8000 attached to a Lachat Instruments XYZ autosampler ASX-500 Series.

4.7.3 Orthophosphate

Samples were diluted appropriately using DI water. The samples were analyzed using flow injection analysis with a Lachat Instruments QuikChem 8000 attached to a Lachat Instruments XYZ autosampler ASX-500 Series.

4.8 Molar ratios

The molar ratios for the three components of struvite are calculated in order to determine the success of reactions. N:P, N:Mg, and Mg:P ratios for each of the three solid "types"

of struvite were calculated using results from aqueous ammonia-N, aqueous orthophosphate, and magnesium data for each experiment.

4.9 Mass balance

Mass balance of total N, P, and Mg in struvite was conducted from raw struvite, heated struvite, through to reformed struvite in solution. The mass balance spreadsheets can be found in Appendix B.

4.10 Heated pellet dissolution in DI water

To quantify the confounding effect of natural pellet dissolution, heated struvite samples were placed in DI water and the pH adjusted to 8-10 and then mixed for 15 minutes to determine how much of the pellet dissolves when no feed solution is present. The concentration of the three struvite components was measured in the water and mass balance was also calculated.

4.11 Elemental analysis (EA)

Elemental Analysis was conducted on solid samples of heated struvite, uptake struvite, and fine struvite. The percent of C, H, and N was determined using the UBC Chemistry Departments FISONS Instruments EA1108 equipped with an AS-200LS autosampler, a combustion oven packed with oxidation catalyst and metallic copper wires, a PorapakQ GC column, and a thermal conductivity detector. The structural identity of the sample was identified by simultaneous solution of a system of two equations and two unknowns using Microsoft Excel Solver function as shown in Appendix C. The unknown "x" corresponds to fractional ammonia in the crystal where "x" ranges from 0-1 (Equation

14). The unknown "y" corresponds to the fractional water in the crystal where "y" ranged from 0-6 (Equation 15).

$MgH(NH_3)_xPO_4(H_2O)_y$

% N: (14)X/[(17)X + Mass of $MgHPO_4$ + (18)y] (Equation 14)

% H: [1+2y+3x]/[(17)X + Mass of $MgHPO_4$ + (18)y] (Equation 15)

4.12 Impurities – Total inorganic carbon and elemental analysis

The chemical formula for pure struvite is $MgNH_4PO_4 \bullet 6H_2O$. However, impurities usually make up a small fraction of a pellet. Total Inorganic Carbon analysis was conducted by weighing five grams of solid sample and dissolving into 30 ml of DI water using an ultrasonic mixer. It was found that struvite formed at the Gold Bar Treatment Plant contained approximately 0.03-0.22% carbon. This agrees quite well with elemental analysis, which found that carbon accounts for 0.18-0.35 % of the total mass.

4.13 Scanning electron microscopy (SEM) analysis

The surface morphology of struvite pellets were examined by scanning electron microscope, using the UBC Materials Engineering Hitachi S-3000N SEM. The pellet sample was placed in epoxy resin and left to cure, followed by polishing. The oval shaped pellet was polished down so that the interior of the struvite was exposed at the surface of the resin holder.

5 Results and discussion

The results of both heating experiments and uptake experiments for both 2009 and 2010 research seasons are given. Comparison to prior research is outlined accordingly.

5.1 Thermal decomposition

It is important to understand the mechanism of ammonia and water loss during heat treatment in order to begin optimizing this ammonia recovery technology. Three complementary approaches were utilized to understand the mechanism including: mass loss curves, solid elemental analysis, and wet-chemical analysis (orthophosphate, ammonium-N, and total magnesium).

5.1.1 Mass loss curves

The mass loss of heated struvite was analyzed using thermogravimetric analysis (TGA) after 24 hour isothermal heat treatment in a thermostatted oven. A TGA was run at 1°/min under moist atmospheric conditions (ie. STP). The total percent mass remaining after the end of the TGA run was 50.41% as shown in Figure 3. This is quite close to the theoretical value of 48.98% for the conversion of magnesium ammonium phosphate hexahydrate to magnesium hydrogen phosphate (Frost et al., 2004). However, a temperature program of 1°/min is not representative of the heating conditions applied when heating batches of struvite for re-use. In this research, batches of struvite were isothermally heated in a pan in a thermostatted oven for 24 hours. The mass loss curves (calculated as percent mass remaining) for six different 24 hour isothermal treatments are also shown on Figure 3. A large gap exists between the mass remaining for the struvite that was isothermally heated at 80°C and 105°C, and the corresponding mass remaining

at these two temperatures on the TGA curve. The discrepancy is likely a result of the slow kinetics of thermal decomposition of struvite and is termed an "isothermal effect." The temperature program in the TGA is too fast and does not give an accurate representation of the true thermodynamic decomposition temperature. In general, thermal decomposition depends on temperature, time, pan size and shape, and chemical makeup, as well as heat transport physics. With a perfectly designed oven and infinite heating duration, it is likely that the decomposition temperature for struvite falls in the range of 60-80°C. Wang et al. (2006) also find that the decomposition temperature lies between 60-100°C.

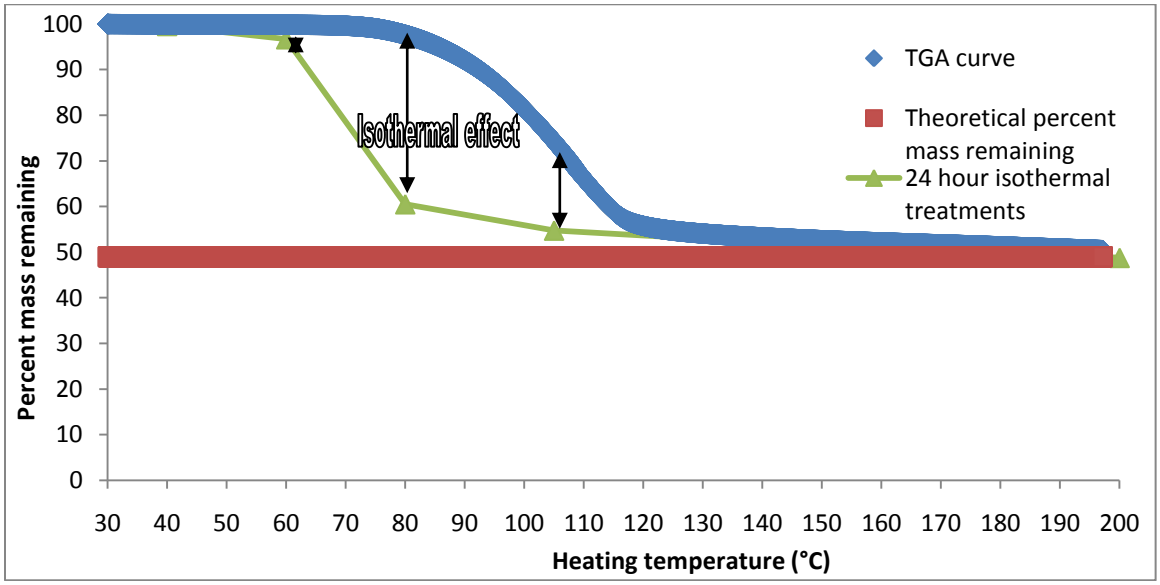

Figure 3 Struvite TGA curve – Percent mass remaining versus temperature.

5.1.2 Mass gain versus time

Heated struvite loses a large amount of water when heated and, therefore, has potential to gain mass when sitting on a table for a long period of time. Figure 4 shows the mass gain effect over a period of two weeks or greater sitting on a lab bench. The first point on each curve is the mass remaining immediately after being taken out of the oven. The

calculated mass increases are tabulated and range from 0-25% (Table 5). The two lowest heating temperatures show hardly any change in mass over time. However, between 80°C and 200°C, the mass recovery becomes much larger, reaching about 25%. The mass recovery is quite stable and does not seem to increase much further after approximately four days.

Calculations were also performed to determine the theoretical percent mass remaining in struvite for each additional water molecule that may become attached to an initially completely amorphous newberyite molecule (Table 6). This represents the possible "bulk sample" structural identity. The term "bulk sample" is defined as the average chemical composition of the sample. For the sample heated to 80°C, it appears that, immediately after heating, struvite has been converted to magnesium hydrogen phosphate monohydrate ($MgHPO_4 \bullet H_2O$) (Figure 4 and Table 6). After atmospheric exposure, it appears that the mineral identity reverts closer to newberyite ($MgHPO_4 \bullet 3H_2O$) (Figure 4 and Table 6). The sample heated to 105°C appears to exist as $MgHPO_4 \bullet H_2O$ immediately after heating, with conversion to $MgHPO_4 \bullet 2H_2O$ after two weeks. The samples heated to 160°C and 200°C appears to exist as amorphous newberyite ($MgHPO_4$) immediately after heating with conversion to $MgHPO_4 \bullet 2H_2O$ after two weeks. These observed mass gains are hypothesized to be attributed to water absorption into the crystals, but were tested further using elemental analysis. In all cases the product was deduced based on mass only and represents a possible "bulk sample" identity. For example, it is likely that while sitting on the bench, some fraction of molecules become

trihydrated to the known mineral newberyite, while the other fraction does not. This leads to an average composition of a dihydrate, which may not actually exist in nature.

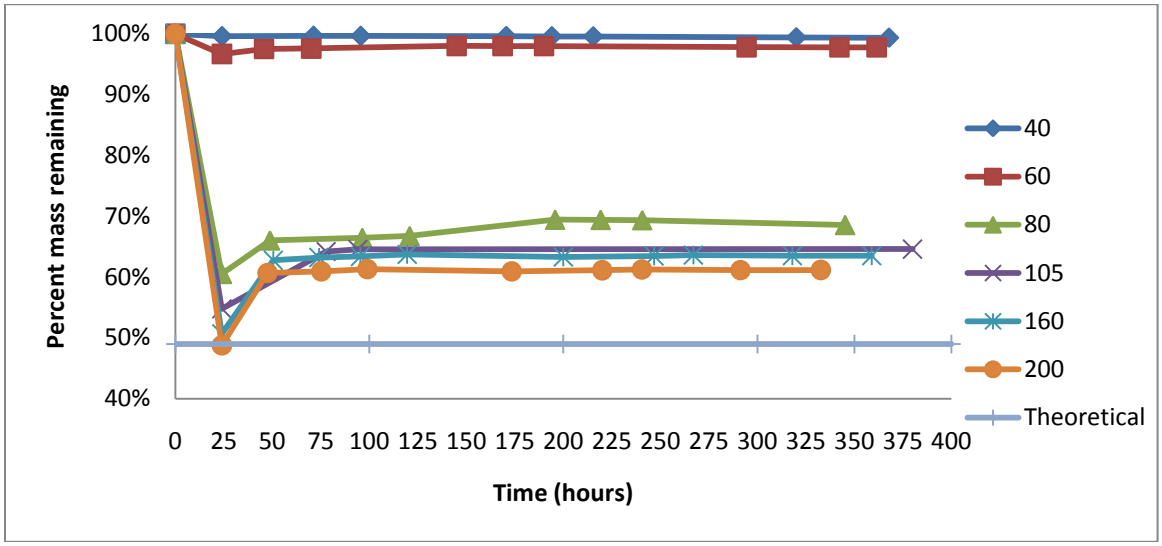

Figure 4 Percent struvite mass remaining over time for six different 24-hour heat treatments.

Table 5 Percent mass recovery after sitting on lab bench for two weeks.

Temperature	Percent mass recovery
40	-0.7
60	1.1
80	13.3
105	18.0
160	25.3
200	25.4

Table 6 Theoretical bulk sample identity after exposure to atmospheric moisture.

Bulk Identity	Mass remaining	Two week water gain
MgHPO4	49%	No water gain
$MgHPO4\bullet1H_2O$	56%	1 water gain
$MgHPO4\bullet2H_2O$	64%	2 water gain
$MgHPO4\bullet3H_2O$	71%	3 water gain

5.1.3 Vacuum desiccation

To prevent the heated pellets from absorbing atmospheric moisture, a vacuum desicator was tested for storage of some samples. The desicator used, however, was unable to

prevent a mass gain (Figure 5). The desicator did slightly reduce the equilibrium mass increase (1.4%) after 48 hours compared to the pellets being stored on the bench (1.7%). Since a better vacuum desicator was unable to be found, its use was abandoned as a method to control heated struvite mass gain over time.

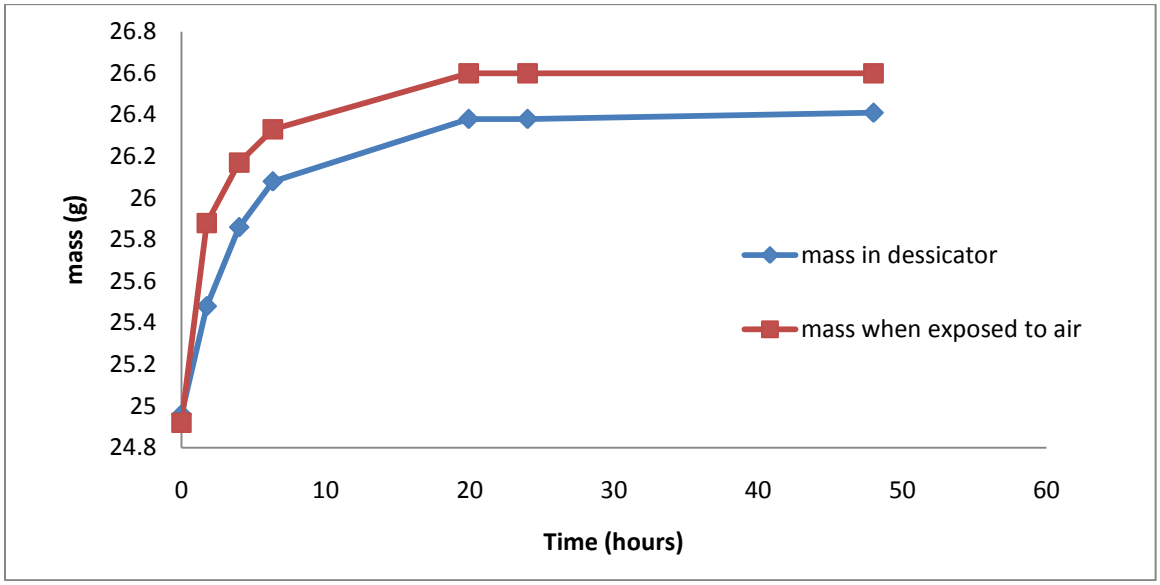

Figure 5 Struvite mass increase over time.

5.2 Elemental analysis

Elemental Analysis of solid samples was conducted in order to supplement the results of the mass loss experiments. The accuracy of this technique allows for stronger evidence of heated struvite structural identity.

5.2.1 Ammonia content

Elemental analysis results for nitrogen content in heated struvite pellets immediately after heating and after two weeks exposure to atmospheric moisture are shown in Figure 6. Excel solver was used to solve for ammonia content as shown in Appendix C. The lowest

temperature heat treatment does not show any difference in nitrogen content compared to the control sample (Ostara Crystal Green®). Beginning at a temperature of 60°C, the nitrogen content decreased to approximately 80%, and then drops significantly to about 30% when heated to between 80°C and 105°C. Heating at higher temperatures resulted in a drop in nitrogen content to between 13-19%. These results do not agree with Frost et al. (2004), likely because in this research isothermal heating was employed rather than a temperature program.

A paired two-tail t-test found no significant difference ($p>0.05$) in nitrogen content for samples taken immediately after heating compared to samples taken after two weeks of atmospheric exposure. This suggests that the crystals are not labile in terms of nitrogen release. These results are different than those found by Sugiyama et al. (2005), in which all ammonia was lost from struvite dust at 200°C. Perhaps, the interior of a pellet is not as accessible by the heat, and therefore, the bulk pellet contains a residual level of nitrogen.

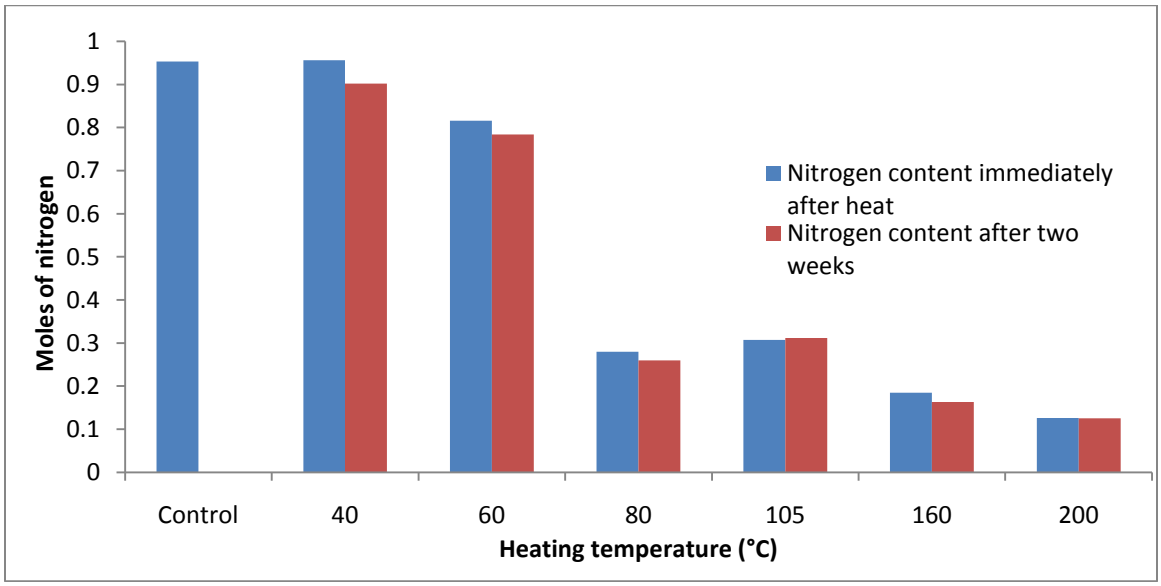

Figure 6 Nitrogen content immediately after heating compared to after two weeks exposed to the atmosphere for six different temperatures and 24 hour duration.

5.2.2 Water content

Elemental analysis was used to determine the hydrogen content in heated struvite pellets immediately after heating, and after two weeks exposure to atmospheric moisture (Figure 7). Similar to nitrogen, 40°C is not hot enough to cause decomposition. However, heating at 60°C causes the crystal to lose one water molecule. This result is inconsistent with mass loss data because one molecule of water theoretically accounts for 7.34% of total mass, but only 3.32% mass loss was observed. This may be explained by taking an elemental analysis sample from a non-homogeneous mixture of heated pellets. It is conceivable that in bulk heating, some portions of pellets are exposed to the heat more than others, resulting in a bulk heating mass loss lower than expected, if all portions of pellets were exposed equally. Heating at 80°C results in a loss of four additional (five total) water molecules. Above 80°C results in additional fractional water release. Approximately 0.18 water molecules remained after 200°C heating. These results do not confirm Sugiyama et al. (2009) who found that $MgHPO_4 \bullet 3H_20$ is produced at heating temperatures of 60°C, or with Wang et al. (2006) who found that struvite is converted to amorphous newberyite at 100°C.. However, the results do confirm Sugiyama et al. (2005) who found that dittmarite is produced upon heating at 100-150°C.

In the range of 80-200°C it was observed that exposure to atmospheric moisture for two weeks resulted in an uptake of between 1.2-1.5 waters. However, as a percent increase, the water increase at each temperature was much different. For 80, 105, 160, and 200°C, the values are 130, 170, 480, and 720%, respectively, suggesting that struvite, heated at higher temperatures, has a greater affinity for atmospheric moisture after being taken out of the oven.

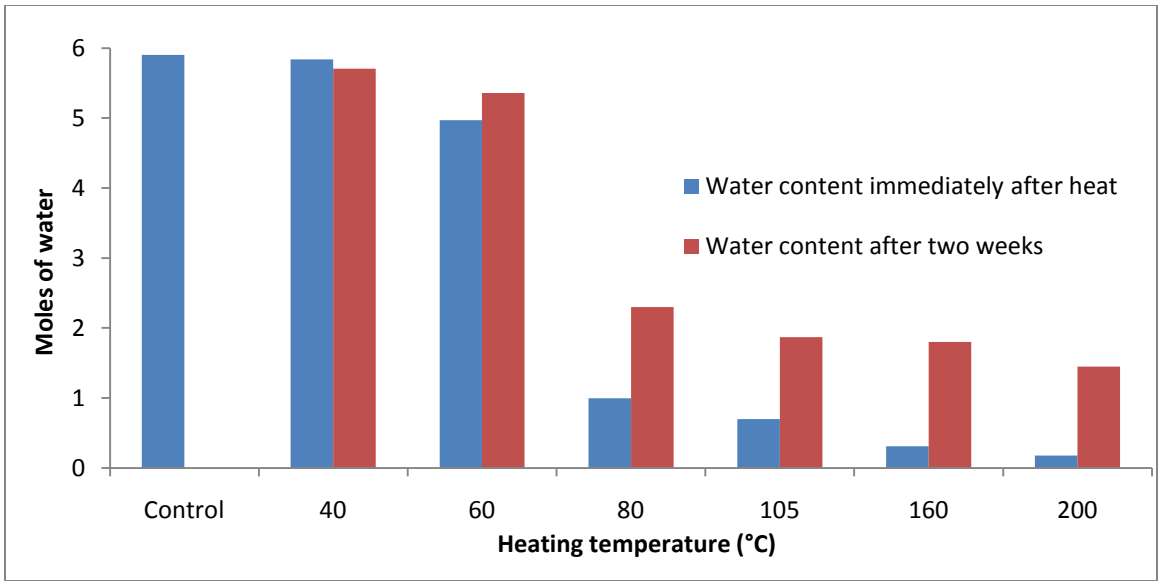

Figure 7 Water content immediately after heating compared to after two weeks exposed to the atmosphere for six different temperatures and 24 hour duration.

5.2.3 Possible chemical identity

The observed mass loss based on the weighing method, and calculated mass loss based on elemental analysis, is in close agreement and is shown in Table 7 and Table 8. A possible chemical formula of pellets heated at each temperature is also presented. The ammonia content is fairly stable across all samples, whereas the water content increases in the samples that were heated at temperatures at 60°C or above.

Table 7 Observed and calculated mass loss and possible chemical formula immediately after heating.

Temperature	Observed loss	Calculated loss	Possible chemical formula
Room "control"	N/A	1.1%	$MgHPO_4(NH_3)_{0.95}(H_2O)_{5.90}$
40	0.4%	1.5%	$MgHPO_4(NH_3)_{0.96}(H_2O)_{5.84}$
60	3.3%	8.9%	$MgHPO_4(NH_3)_{0.82}(H_2O)_{4.97}$
80	39.5%	41.7%	$MgHPO_4(NH_3)_{0.28}(H_2O)_{1.00}$
105	45.2%	43.7%	$MgHPO_4(NH_3)_{0.31}(H_2O)_{0.70}$
160	49.3%	47.4%	$MgHPO_4(NH_3)_{0.19}(H_2O)_{0.31}$
200	51.2%	48.8%	$MgHPO_4(NH_3)_{0.13}(H_2O)_{0.18}$

Table 8 Observed and calculated mass loss and possible chemical formula two weeks after heating and exposure to the atmosphere.

Temperature	Observed loss	Calculated loss	Possible chemical formula
Room "control"	N/A	1.1%	$MgHPO_4(NH_3)_{0.95}(H_2O)_{5.90}$
40	0.7%	2.8%	$MgHPO_4(NH_3)_{0.90}(H_2O)_{5.71}$
60	2.2%	6.2%	$MgHPO_4(NH_3)_{0.78}(H_2O)_{5.36}$
80	31.4%	32.3%	$MgHPO_4(NH_3)_{0.26}(H_2O)_{2.30}$
105	35.4%	35.1%	$MgHPO_4(NH_3)_{0.31}(H_2O)_{1.87}$
160	36.5%	36.6%	$MgHPO_4(NH_3)_{0.16}(H_2O)_{1.80}$
200	38.8%	39.5%	$MgHPO_4(NH_3)_{0.13}(H_2O)_{1.45}$

5.2.4 Environment effects on ammonia and water content

The chemical composition of pellets placed in DI water for 5 minutes was tested using elemental analysis to see if any change occurs upon introduction of heated pellets into solution. Figure 8 shows that the ammonia content stays fairly stable upon placement in water except for the sample that had previously undergone isothermal heat treatment at 105°C. This may be due to the solubility of heated struvite. However, this effect was not observed at the other two temperatures.

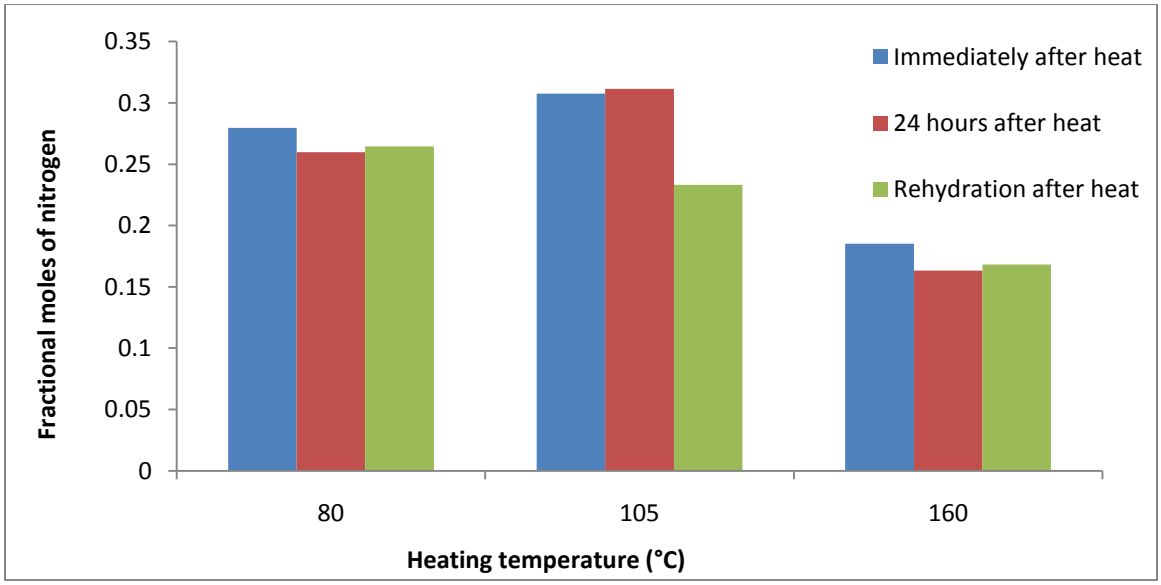

Figure 8 Effect of heating temperature on struvite nitrogen content for three different environments.

The water content increases for all three temperatures when placed in DI water (Figure 9). This is expected as heated pellets are surrounded by water allowing for crystallization in areas of the crystal that was previously water deficient. The pellets probably do not re-attain a molar water value of six because of the very short reaction period.

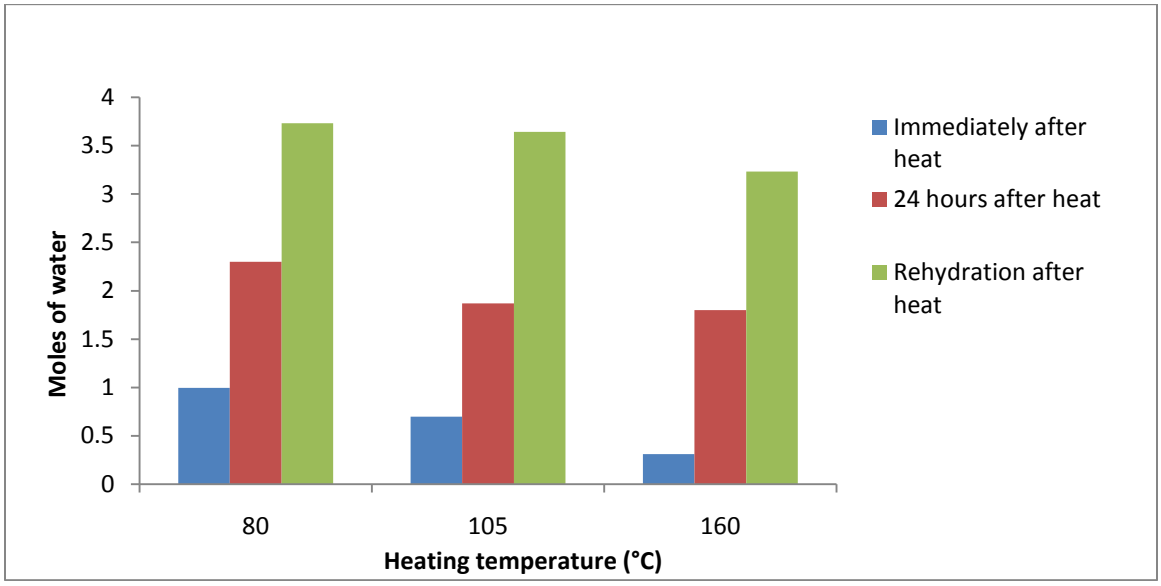

Figure 9 Effect of heating temperature on struvite water content for three different environments.

5.2.5 Comparing heated pellets to uptake pellets

The three samples above were compared to a full batch of struvite (80g/L) that was rehydrated in DI water for 15 minutes, and a full batch of struvite (80g/L) that was placed in the synthetic ammonium solution at pH 8 for two hours. The ammonia content of the full batch of rehydrated struvite was slightly lower compared to struvite that has been heated only (Figure 10). This may be due to some dissolution of the pellet, releasing ammonium into solution. However, the pellets that were exposed to the synthetic ammonium solution resulted in a slight increase in nitrogen content. Dissolution of the pellets may be a source of magnesium and phosphate which can subsequently react with ammonium in the synthetic solution to reform new "fine" struvite that attaches to the

surface of the pellet. This mechanism, known as “dissolution-reformation (DR),” was also found by (Sugiyama et al., 2005).The validity of this hypothesis is supported by the nitrogen content in the fines that was close to the theoretical struvite value of one.

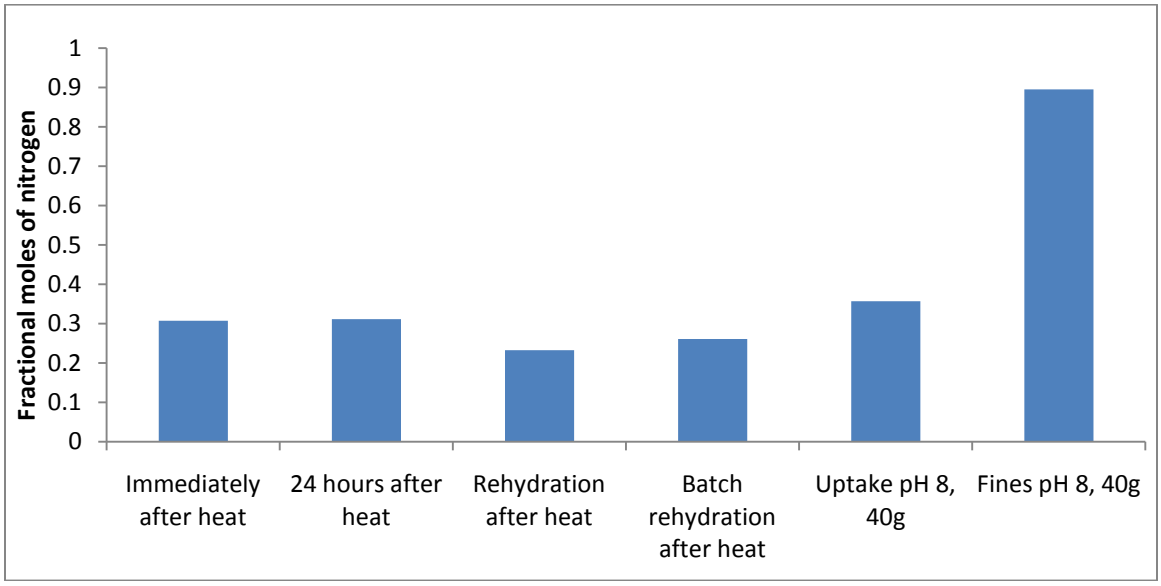

Figure 10 Effect of different environments on the nitrogen content in struvite heated at 105°C.

Approximately four moles of water exist in the structure of the rehydrated pellets and the “uptake” pellets (Figure 11). However, the fine crystals contain a water content of about 5.7 moles, which is closer to the theoretical pure struvite value. The “uptake” pellets and the fines both came from the same source of heated struvite and were subject to the exact same experimental conditions during the two hour exposure to synthetic ammonium solution. It is logical to assume that both solids had the same water content. Since this was not observed, the evidence in favour of a DR mechanism is strengthened.

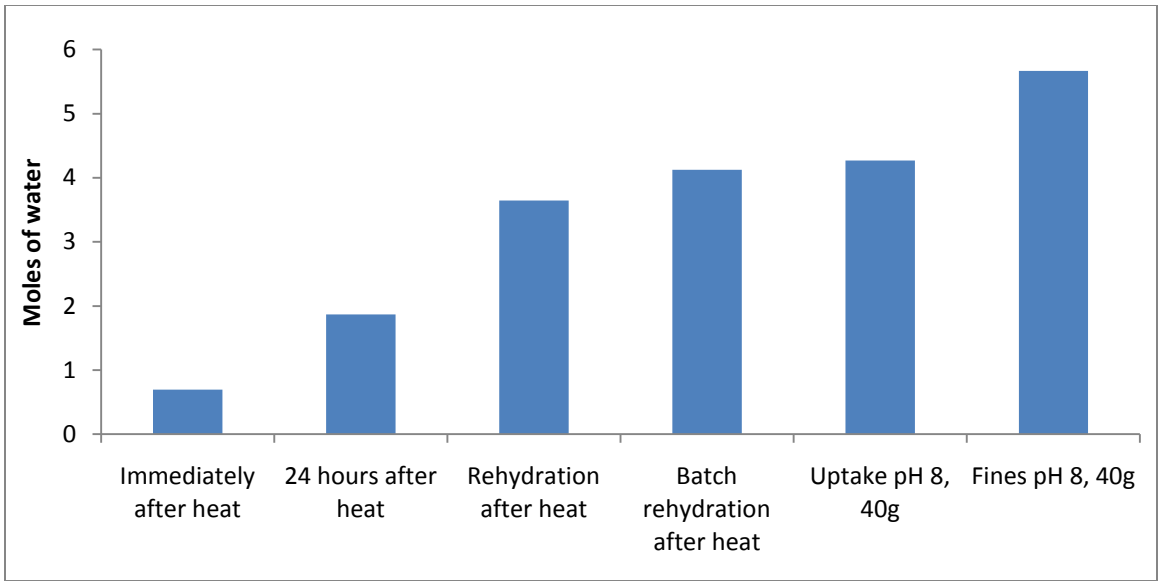

Figure 11 Effect of different environments on the water content in struvite heated at 105°C.

All of the structures based on elemental analyses are compared in Table 9. It is most important to note that both the nitrogen and water content of pellets exposed to DI water and the pellets exposed to synthetic solution were very similar, whereas the fines have a chemical structure much closer to theoretical struvite.

Table 9 Structure comparison.

"Type" of struvite	Possible chemical formula
Heated struvite	$MgHPO_4(NH_3)_{0.31}(H_2O)_{0.70}$
Heated struvite after 24 hours exposure	$MgHPO_4(NH_3)_{0.31}(H_2O)_{1.87}$
Rehydration in DI H_2O	$MgHPO_4(NH_3)_{0.26}(H_2O)_{4.12}$
Uptake	$MgHPO_4(NH_3)_{0.36}(H_2O)_{4.27}$
Fines	$MgHPO_4(NH_3)_{0.90}(H_2O)_{5.67}$

5.3 Wet-chemical analysis – Molar ratios

A small amount of heated struvite samples were dissolved and analyzed for the magnesium, nitrogen, and phosphorus concentrations. Molar ratios were calculated (N:P,

N:Mg, and Mg:P). Struvite immediately after 24 hour isothermal heating and for the same sample after being exposed to the atmosphere for two weeks was compared.

5.3.1 N:P ratio

The N:P ratio was near unity up to 60°C (Figure 12). Between 80°C and 105°C, the N:P ratio drops to approximately 0.3 as ammonia is released from the crystal. Fumoto et al. (2009) also find that ammonia content drops to 0.3 when heated in an oven at 105°C. The N:P ratio decreased further to 0.22 and 0.16 for heating at 160°C and 200°C, respectively. The trend of results of these wet-chemical analyses is similar to the trend of the results using the elemental analysis method. However, at 160 and 200°C the elemental method yielded slightly smaller nitrogen contents compared to the N:P ratio calculated from wet-chemical analyses. For 60°C, the nitrogen content, using elemental analysis, was 0.15 moles less than the wet-chemical method. A plausible explanation may be that acid dissolution is unable to dissolve all of the phosphate in the pellets, leading to a N:P ratio that is biased high. This comparison is also complicated by the fact that absolute nitrogen content (elemental analysis) is being compared to relative nitrogen content (N:P ratio).

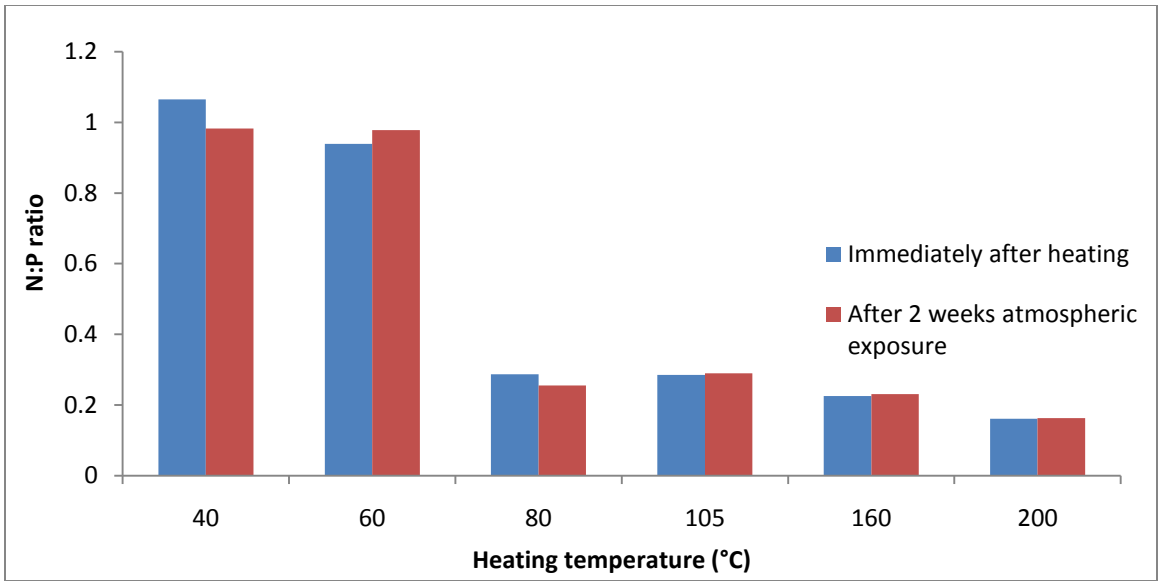

Figure 12 N:P ratio comparison of pellets immediately after heating and after 2 weeks exposure to atmospheric moisture.

5.3.2 N:Mg ratio

Figure 13 shows the N:Mg ratio for the same set of samples. The same trend was observed as in the N:P ratio. This result is expected as both Mg is non-volatile.

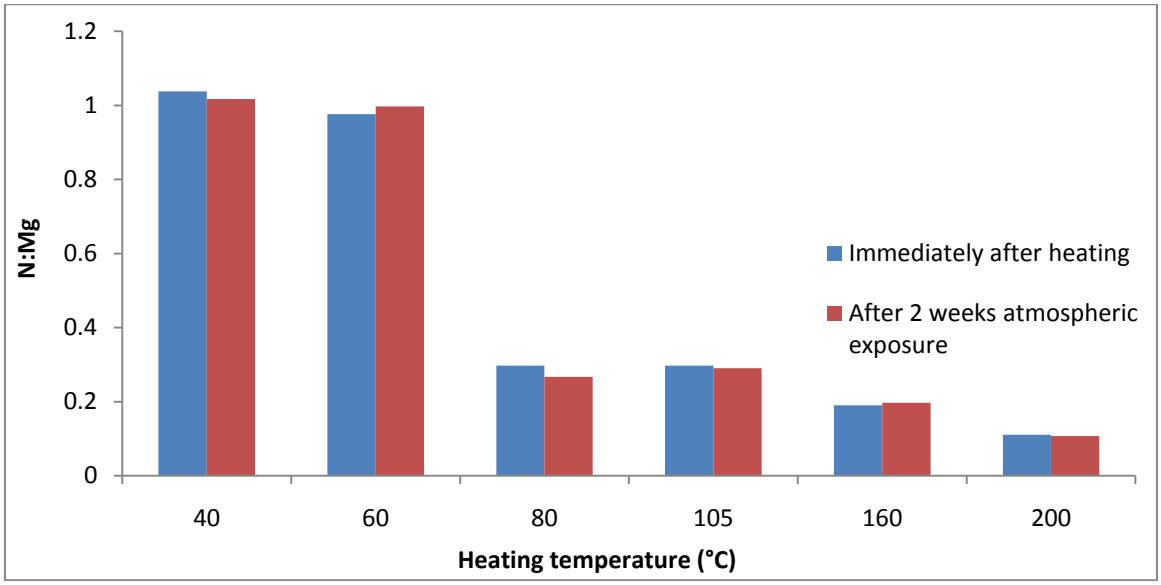

Figure 13 N:Mg ratio comparison of pellets immediately after heating and after 2 weeks exposure to atmospheric moisture.

5.3.3 Mg:P ratio

Both magnesium and phosphorus don't have a gaseous form and cannot escape the crystal when heated. Therefore, the Mg:P ratio was expected to be close to unity across all temperatures. The samples heated between 40°C to 105°C have the expected Mg:P ratio of 1 (Figure 14). The ratio observed at 160°C and 200°C was 1.2 and 1.45, respectively. This deviation was unexpected and suggests that a chemical conversion is occurring during thermal decomposition in this temperature range. Perhaps some phosphate is converted to pyrophosphate, which is much harder to dissolve in the acid used. Effectively, this reduces the amount of phosphorus that the analyzer can detect, resulting in an increased Mg:P ratio.

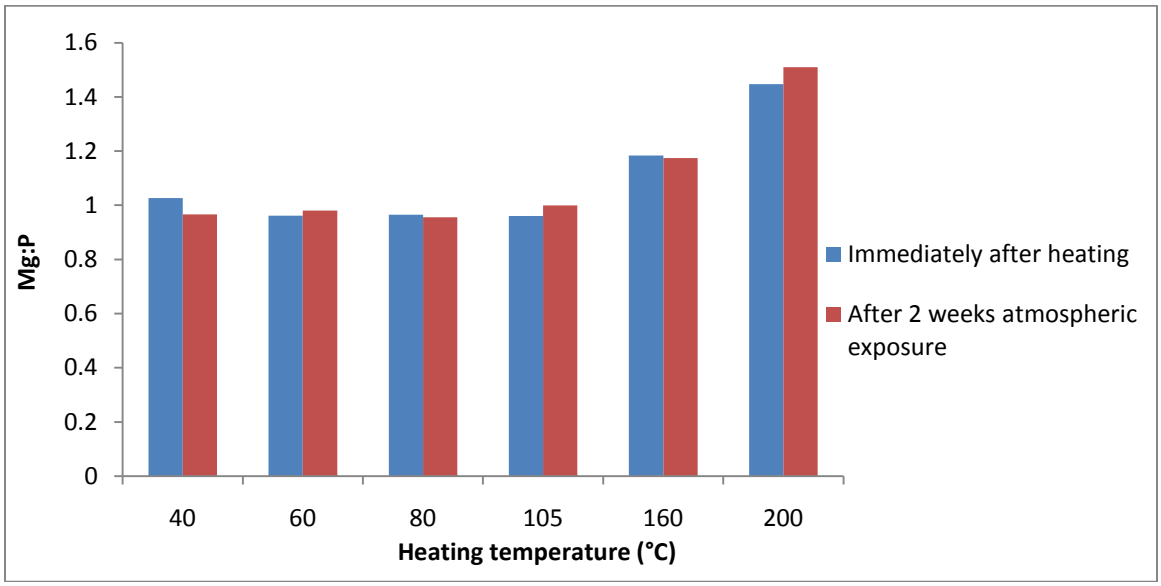

Figure 14 Mg:P ratio comparison of pellets immediately after heating and after 2 weeks exposure to atmospheric moisture.

5.4 Bulk sample heating

Large samples of struvite (~120-150g) were isothermally heated for 24 hours in an aluminum pan. Percent remaining and molar ratios are calculated below.

5.4.1 Percent mass remaining

In general, less mass remained as the temperature of isothermal heating increased (Figure 15). However, the trend is not followed for the 120°C, 180°C, and 200°C. Many experimental conditions were not controlled. These experiments were carried out over a two year period, using different pans and different ovens, which may explain some variation. Also, it is likely that the samples at 180°C and 200°C were able to absorb atmospheric moisture before the weight was recorded, causing a biased high result.

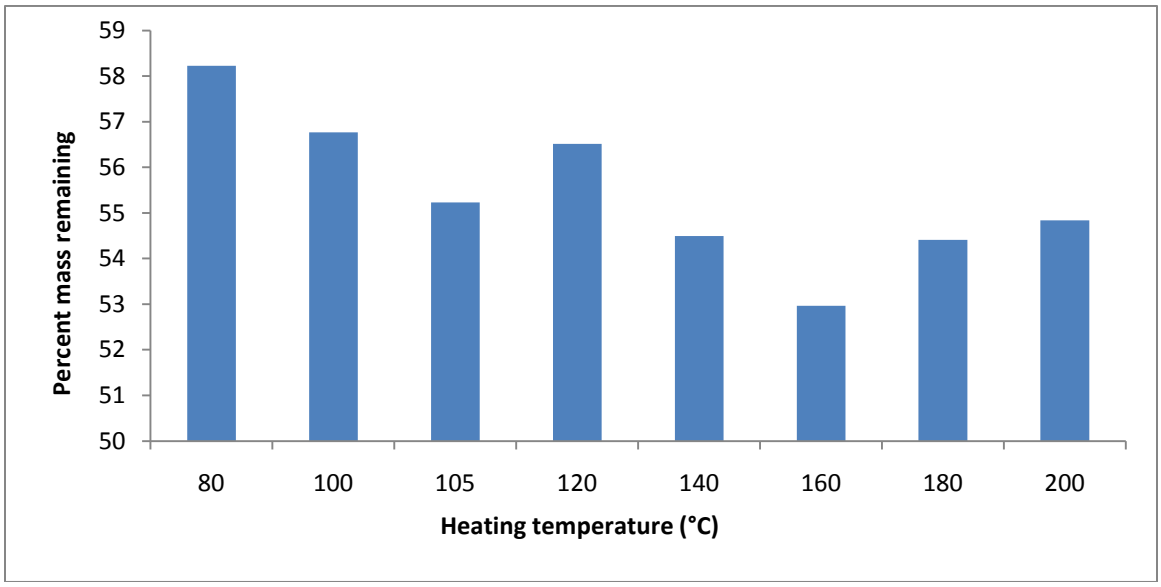

Figure 15 Percent mass remaining after 24 hours heating.

5.4.2 Comparison of crushed and pelletized struvite from Lulu Island WWTP and Edmonton Alberta Gold Bar WWTP

It was hypothesized that the surface area exposed to heat was a limiting factor in struvite mass loss and chemical transformation. For temperatures between 100°C -120°C, a comparison of the mass loss versus time for struvite in pellet form and crushed pellets indicates that surface area is not a key factor limiting the water and ammonia removal from a struvite crystal (Figure 16-18). This is surprising because thermal decomposition

is controlled by heat transfer, which increases as the surface area to volume gets larger. However, due to the long heating duration, heat transfer may no longer play an important role, resulting in near equal thermal decomposition profiles for different morphologies. This is further confirmed by the observation that the majority of mass loss occurred within the first hour of heating.

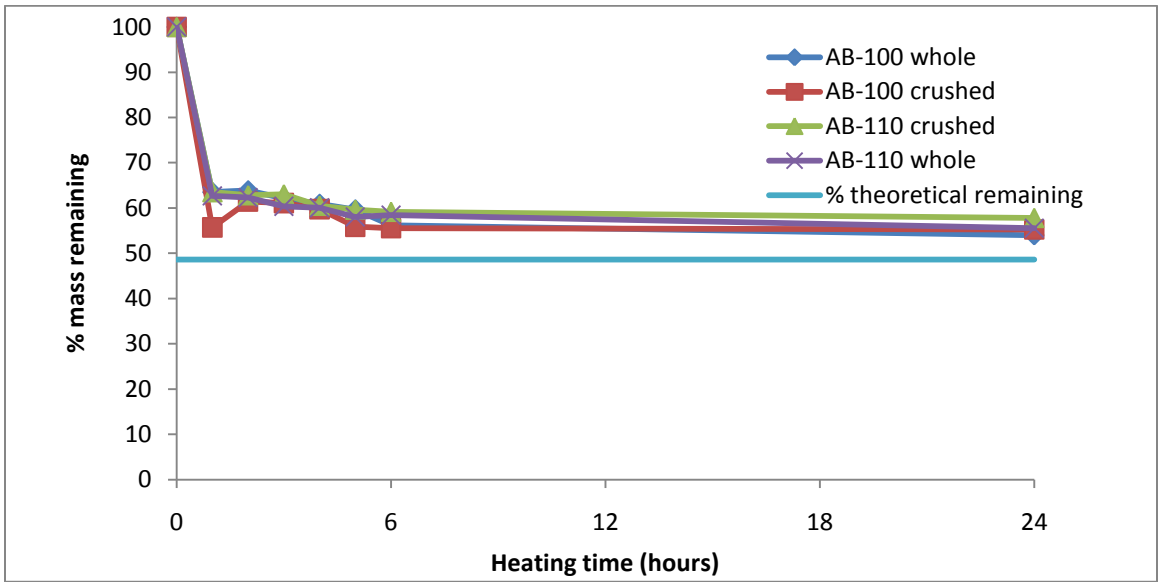

Figure 16 Percent mass remaining versus time comparing size and morphology at a heating temperature of 100°C.

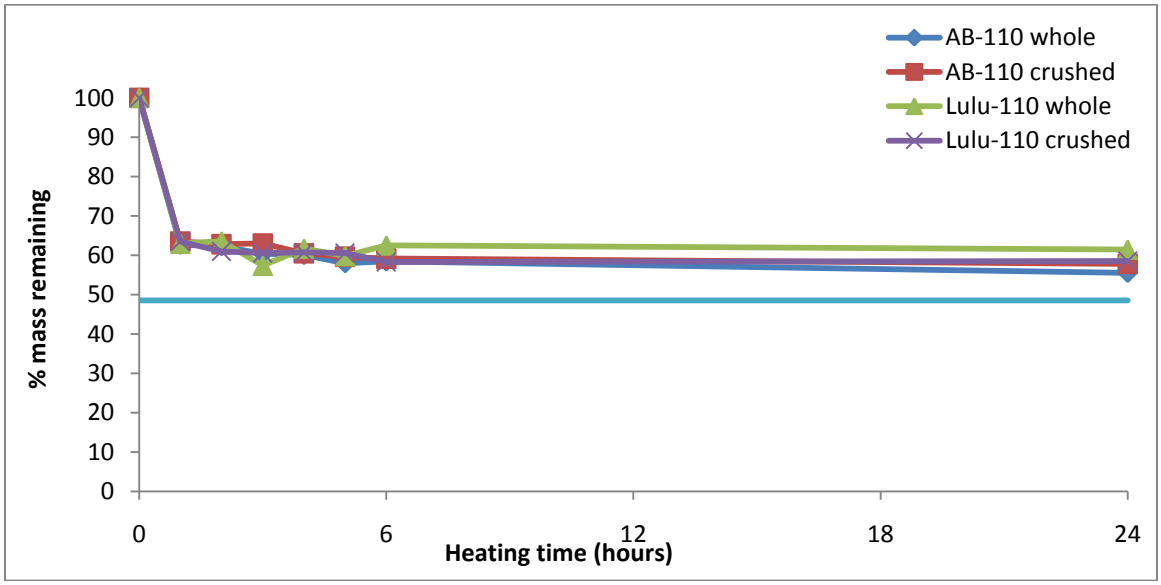

Figure 17 Percent mass remaining versus time comparing size and morphology at a heating temperature of 110°C.

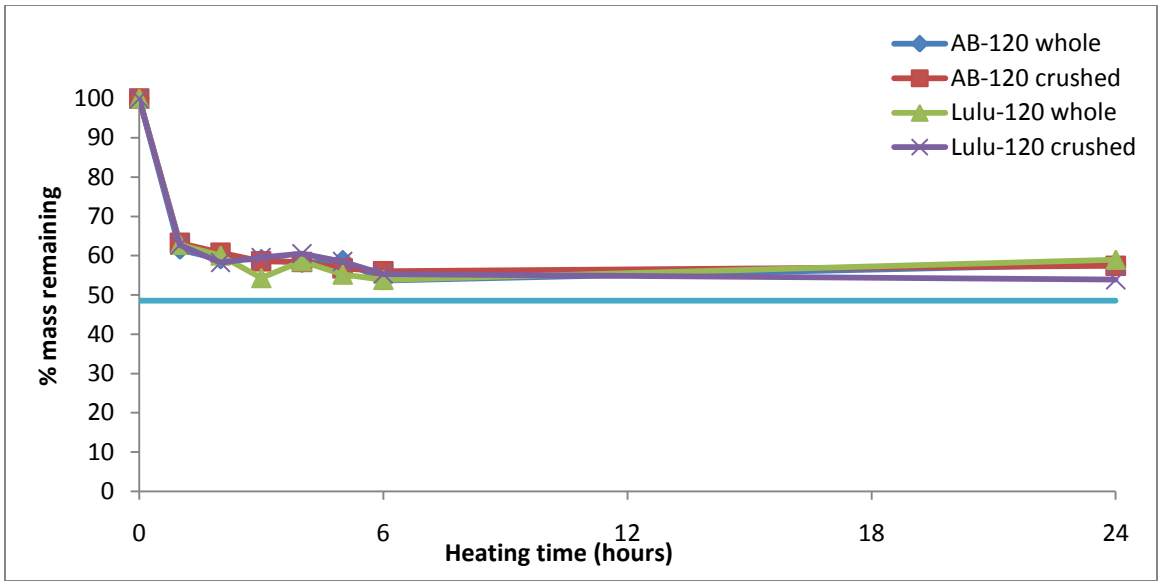

Figure 18 Percent mass remaining versus time comparing size and morphology at a heating temperature of 120°C.

5.4.3 Time to achieve chemical transformation

Separate struvite samples were heated at 30 minute intervals until three hours had elapsed and the remaining samples were heated at 60 minute intervals up to 6 hours. This procedure was carried out at four different temperatures ranging from 100°C to 140°C. The Mg:P ratios (Figure 19) were expected to remain unity as Mg and P are not non volatile. This was observed for the three lowest temperatures, but not for the highest temperature. This is likely due to the difficulty in dissolving phosphorus that may have been converted to pyrophosphate during heating at 140°C. The N:P ratio declined to 0.3-0.4 after 30 minutes of heating (Figure 20). The N:P ratio declined slightly further to 0.23-0.26 if the samples remained in the oven up to six hours. The same trend was observed in the N:Mg ratios (Figure 21). It appears that ammonia removal is largely complete after 30 minutes of heating at all temperatures. In comparison, Wang et al. (2006) found that heating longer than 2 hours is not cost effective to remove the

remainder of ammonia. This has important implications with respect to energy cost savings associated with heating struvite to remove ammonia.

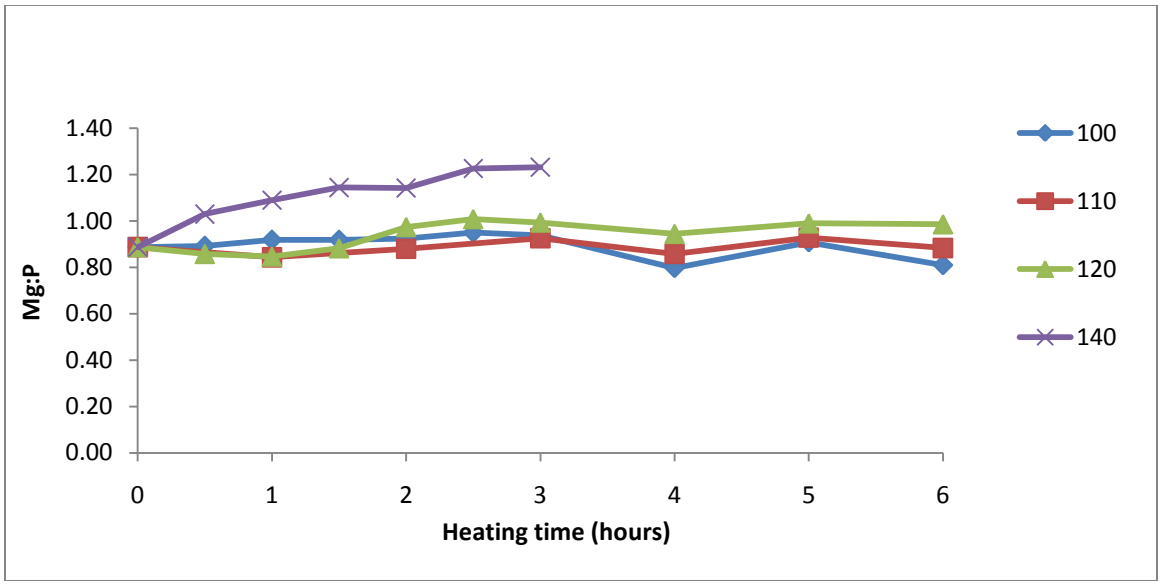

Figure 19 Mg:P vs. heating time for four temperatures.

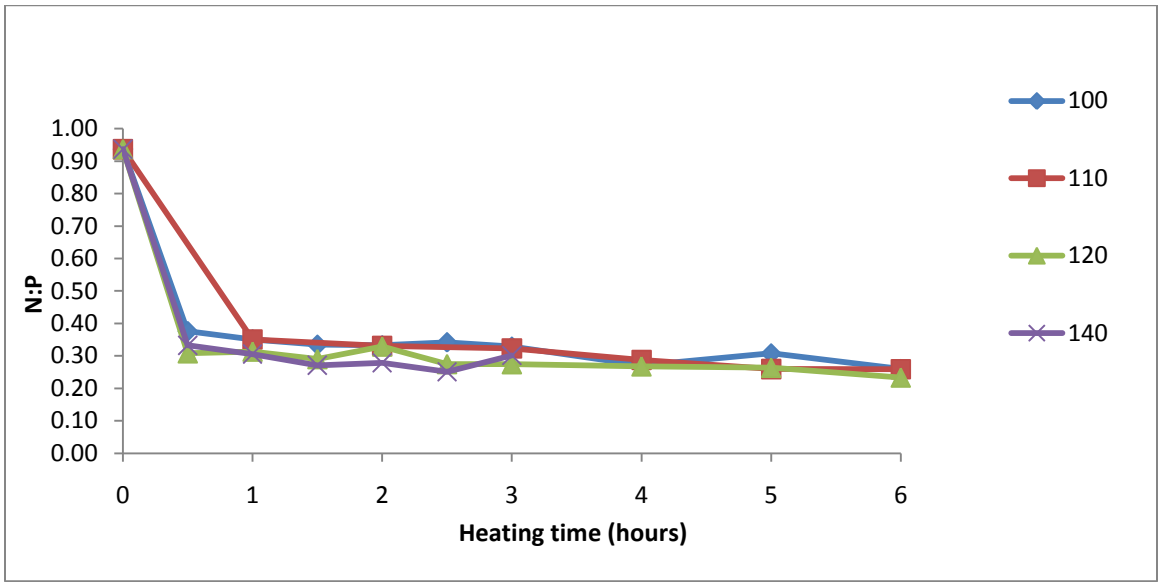

Figure 20 N:P vs. heating time for four temperatures.

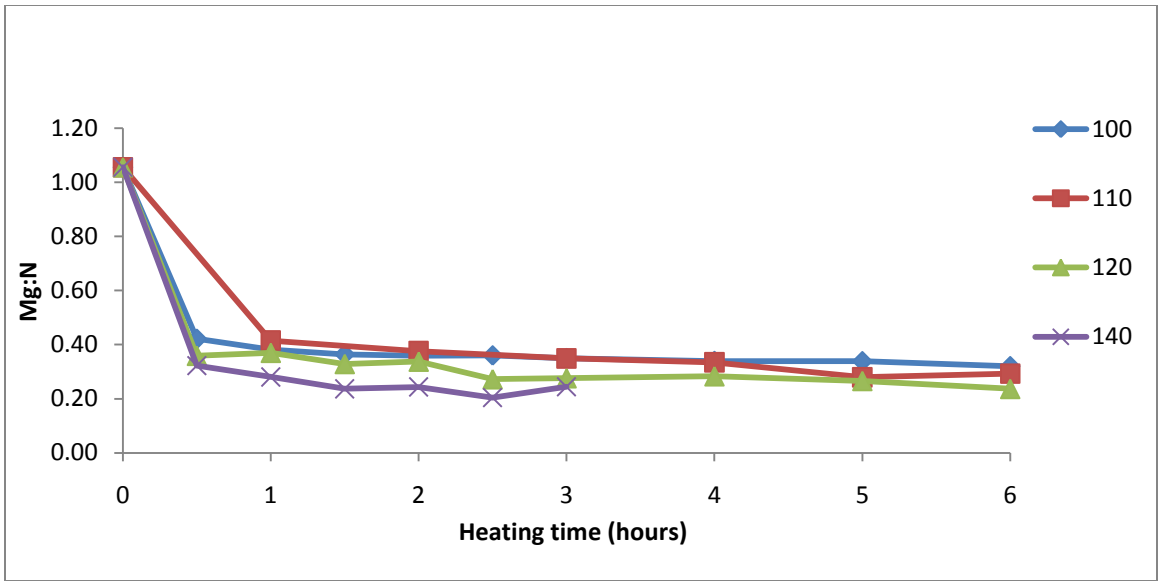

Figure 21 N:Mg vs. heating time for four temperatures.

5.5 Uptake stage one: June 2009-October 2009

The first stage of struvite reformation experiments were conducted over a period of six months in 2009. Raw struvite from Edmonton, Alberta Gold Bar WWTP was isothermally heated at six temperatures (between 100°C-200°C) for 24 hours, to remove ammonia from the crystal. Struvite samples were subsequently placed in the synthetic ammonium feed at three different pH values (8, 9, and 10). These 24 combinations were used to determine the most effective heating temperature and solution pH to achieve maximum ammonium removal, while simultaneously maintaining pellet shape and strength. The struvite reformation reactions were completed over a period of 2 hours, with aqueous samples being taken every 15 minutes.

5.5.1 Ammonium profile

The ammonia profile versus temperature of heating is discussed below. Experiments were conducted at three different constant pH values and compared.

5.5.1.1 Total ammonia concentration versus time at pH 8

The ammonia removals after 2 hours ranged from 91-98% (Figure 22). In general, ammonia removal was faster for struvite that was heated to higher temperatures. However, for struvite heated at 200°C, the trend was not followed. The relatively poor ammonia removal within the first 30 minutes may be explained by the greater solubility that the struvite has when heated at high temperatures. It is possible that the product is thermodynamically unstable and dissolves easily in water, releasing ammonium ions that were previously bound within the crystal. In general, a two hour reaction duration was required to reduce ammonia concentrations by 90% for struvite heated at low temperatures. The required reaction duration was only one hour for struvite heated at higher temperatures. This reduction in required reaction time is likely due to the higher solubility of struvite heated at higher temperatures. This means that struvite is a source of magnesium and phosphate and reacts with the excess ammonia, forming struvite more quickly.

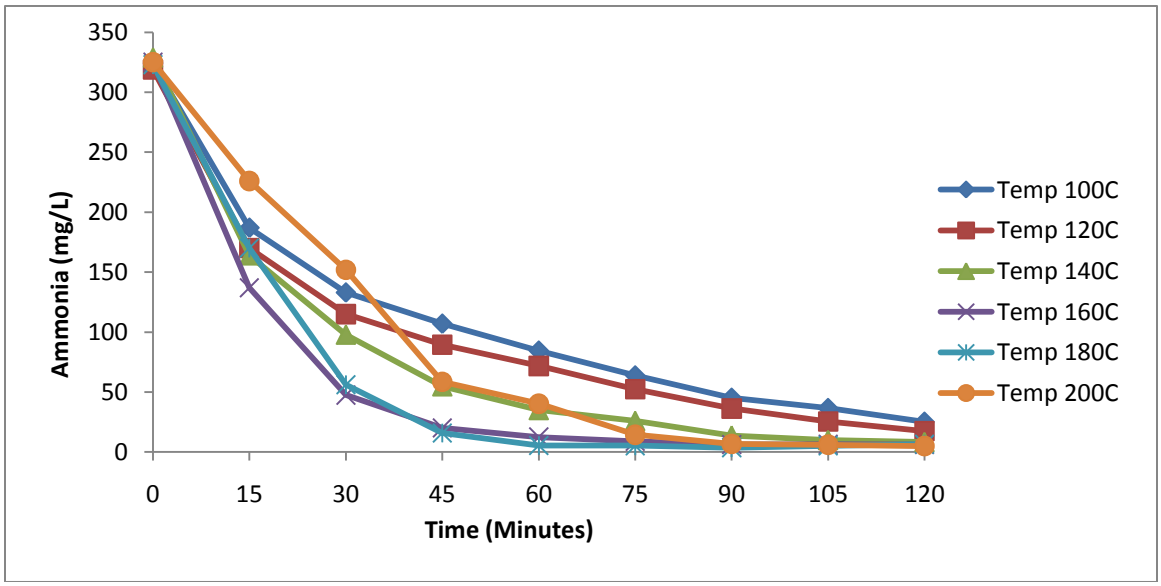

Figure 22 Ammonia concentration for Gold Bar struvite at pH 8.

5.5.1.2 Total ammonia concentration versus time at pH 9

A similar total ammonia concentration versus time profile occurred for the samples that underwent the struvite reformation reaction at pH 9 (Figure 23). The major difference observed was the flatter shapes of the ammonia concentration versus time curves. At the 100°C heating temperature, only 48% ammonia was removed after two hours, whereas 97-99% was removed for the 140°C -180°C heating temperatures. Again, the sample heated to 200°C underperformed, likely as a result of high dissolution.

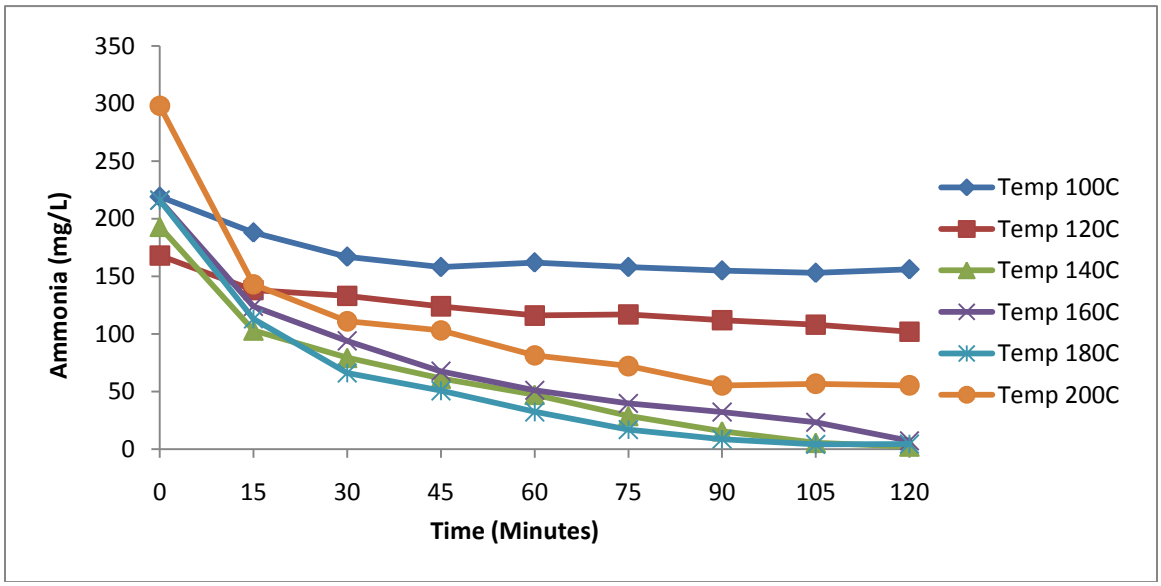

Figure 23 Ammonia concentration for Gold Bar struvite at pH 9.

5.5.1.3 Total ammonia concentration versus time at pH 10

Compared to the pH 9 profiles, the ammonia removals at pH 10 were worse (Figure 24). This is likely due to lower solubility of struvite at higher pH values, retarding the dissolution of the heated pellets, resulting in a lower source pool of magnesium and phosphate ions. The lowest ammonia removals occurred at 100°C and 200°C, with values of only 36% and 48%, respectively. The largest ammonia removals occurred at 140°C and 160°C at 73%.

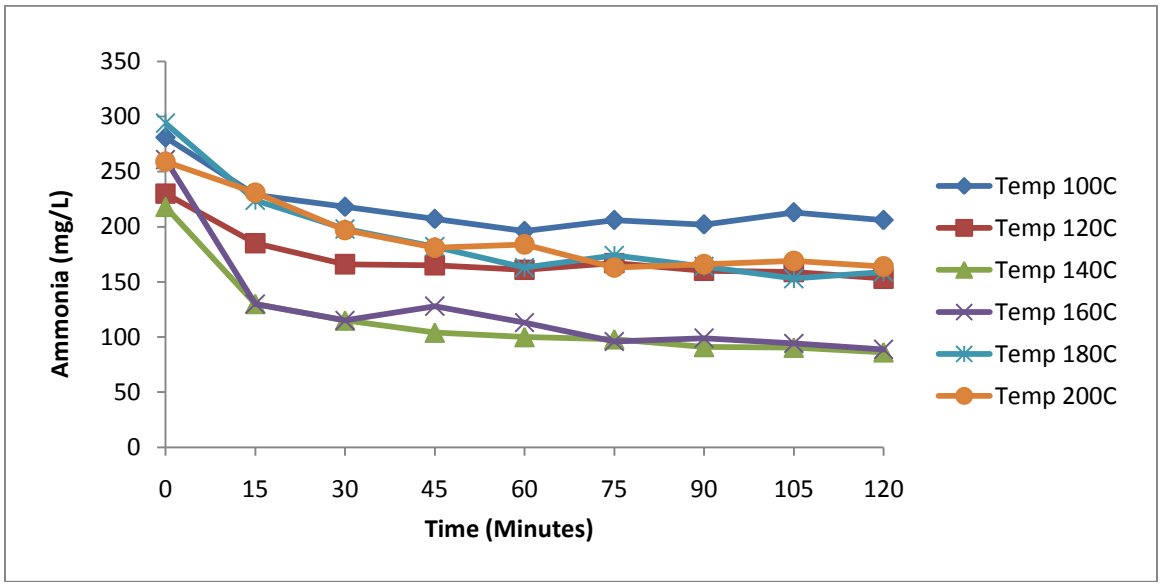

Figure 24 Ammonia concentration for Gold Bar struvite at pH 10.

5.5.1.4 Ammonia removal summary

The results across all three pH conditions suggest that pH 8 is required to achieve the largest ammonia removals (91%-98%). This contradicts both Wang et al. (2006) and Sugiyama et al. (2009), who found that pH 10 results in the best ammonium removal due to a decrease in struvite solubility. If a two hour reaction duration is applied, the temperature that struvite was heated at becomes only a minor factor in ammonia removal. However, if heated at mid range temperatures (140°C -180°C) one hour reaction duration is sufficient. Higher heating temperature generally resulted in better ammonium removals, unlike Fumoto et al. (2009), who observed that higher heating temperature led to less adsorption sites. The ammonia removals are probably lower for reactions conducted at pH 9 and pH 10 because the solubility of struvite is reduced at higher pH values. This means that the fraction of struvite that remains in a heated crystal is thermodynamically stable and will not dissolve and act as a source of magnesium and phosphate, for nascent struvite formation.

5.5.2 Orthophosphate profile

The orthophosphate profile versus temperature of heating is discussed below. Experiments were conducted at three different constant pH values and compared.

5.5.2.1 Orthophosphate concentration versus time at pH 8

The phosphate concentration profiles versus time were plotted at pH 8 for all six temperatures (Figure 25). At all temperatures, the concentration of phosphorus was found to increase over time. Dissolution is a time-dependent process and, therefore, the longer the pellets stay in solution the more they are able to dissolve, so that the solution can achieve saturation with respect to struvite. It was interesting to find that the lowest temperatures yield the smallest increase in phosphate concentrations. This result matches with the lowest ammonium removal (Figure 22). Also, the samples heated to 160°C and 200°C show the largest increase in phosphate concentrations, matched with the largest ammonium removals.

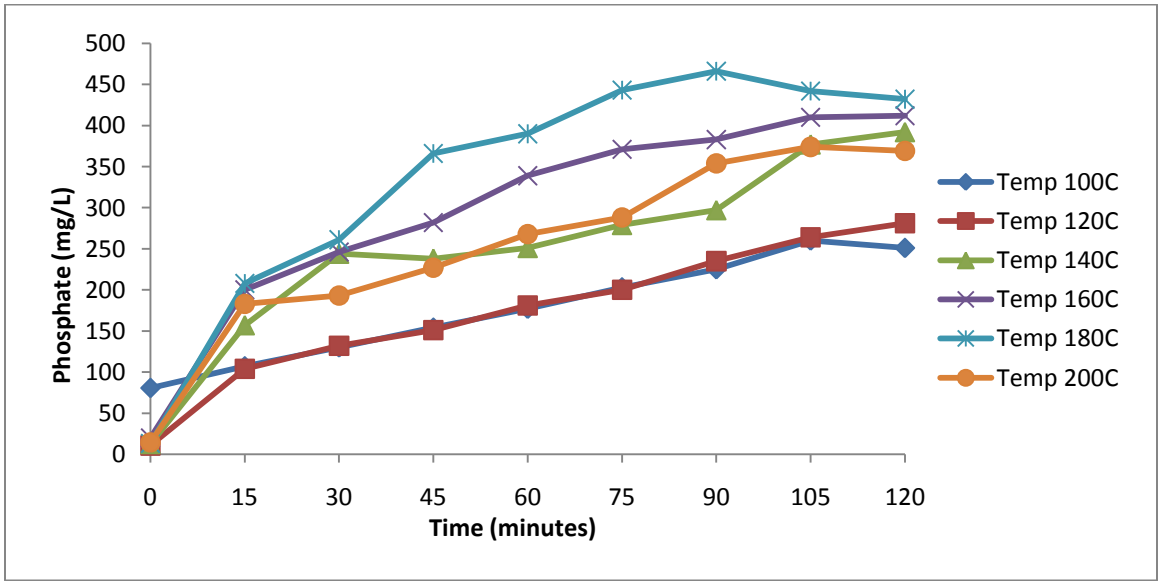

Figure 25 Orthophosphate concentration for Gold Bar struvite at pH 8.

5.5.2.2 Orthophosphate concentration versus time at pH 9

The phosphate concentrations for reactions at pH 9 are lower than compared to pH 8 and do not show as much of a linear increase over time (Figure 26). This is due to the fact that struvite is less soluble at higher pH values. Similar to pH 8, the samples which had the largest phosphate concentrations also had the best ammonium removals. This suggests that heated struvite is a source of phosphate, which is subsequently utilized by excess ammonium to form new struvite.

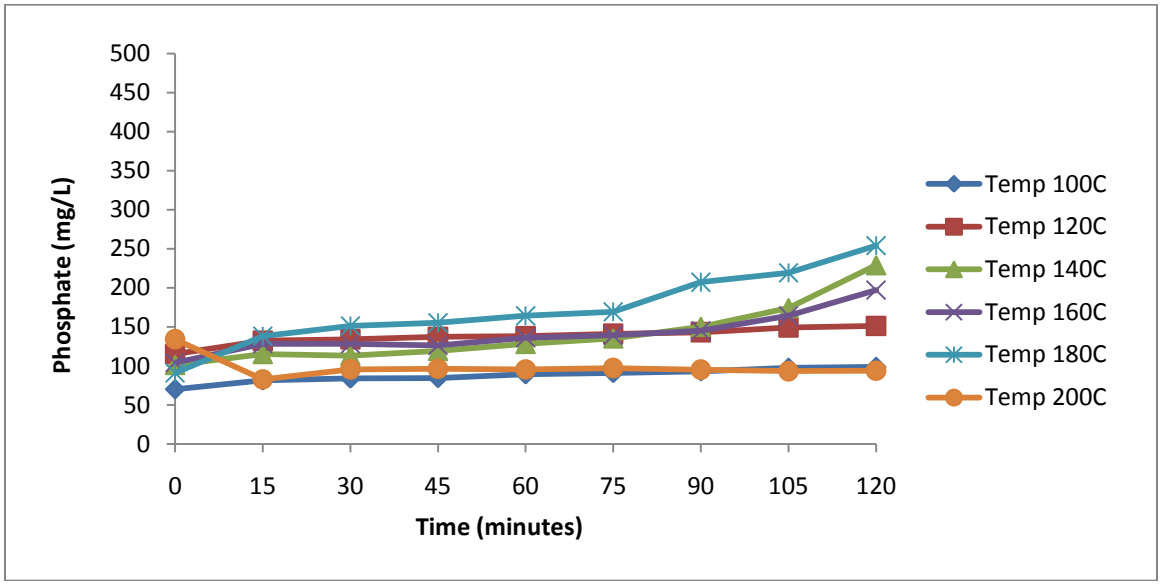

Figure 26 Orthophosphate concentration for Gold Bar struvite at pH 9.

5.5.2.3 Orthophosphate concentration versus time at pH 10

The phosphate concentrations are stable for the duration of the reaction period at pH 10 (Figure 27). For the two highest temperatures, the phosphorus profile decreases versus time, because struvite is highly insoluble at this pH value.

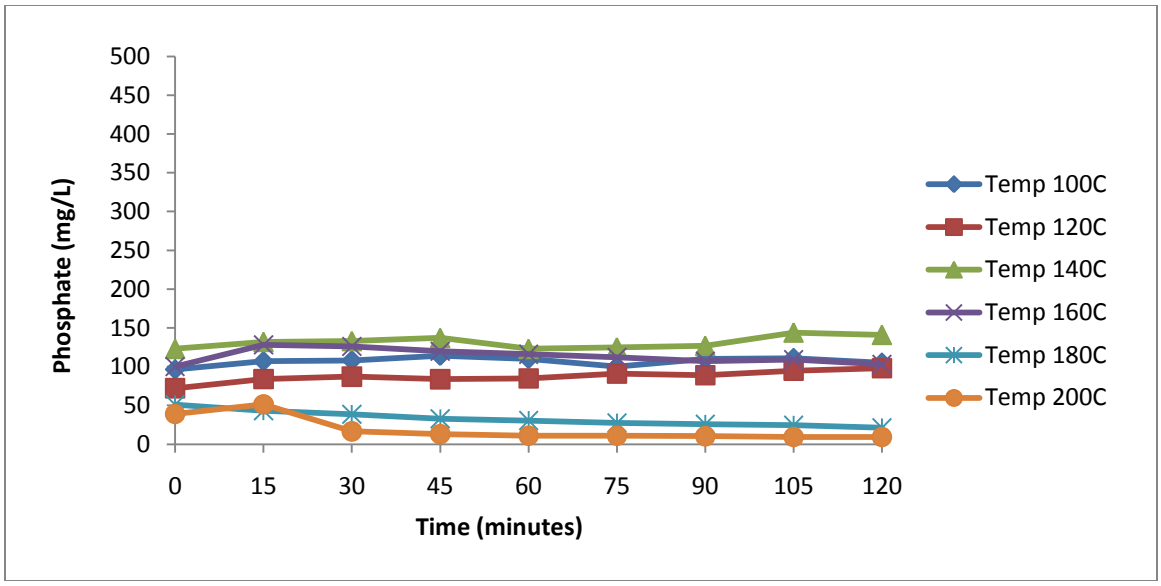

Figure 27 Orthophosphate concentration for Gold Bar struvite at pH 10.

5.5.2.4 Orthophosphate removal summary

In general, phosphorus concentrations increase over time because the solution is undersaturated with respect to struvite; this caused the heated pellets to dissolve. This effect is known as "phosphate release" or "phosphate melting." This process is time dependent and is amplified at lower pH values because heated struvite becomes more soluble. Phosphorus increased in solution by between 1050 to 1850% at pH 8, by 700 to 1900% at pH 9, and by -20 to 900% at pH 10.

It is apparent that a trade off between ammonium removal and phosphate release exists. To achieve the largest ammonium removals, one must be willing to release phosphate from the pellets back into solution. This melting process will be discussed further in the context of new, fine struvite formation.

5.5.3 Magnesium profile

The magnesium profile versus temperature of heating is discussed below. Experiments were conducted at three different constant pH values and compared.

5.5.3.1 Total magnesium concentration versus time at pH 8

The magnesium concentration profiles versus time were plotted at pH 8 for all six temperatures (Figure 28). In general, magnesium concentration increased over time and was larger for struvite heated to higher temperatures. The concentration increase ranged from 70 to 2350%. Heated struvite pellets are a source of magnesium and the solubility increases with the degree of dehydration.

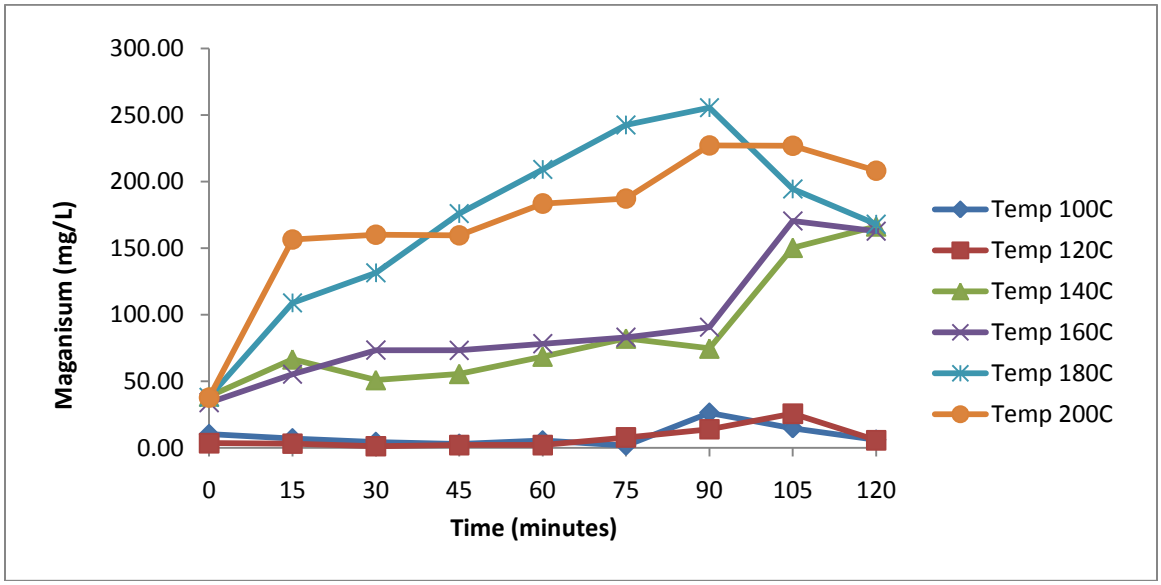

Figure 28 Magnesium concentration for Gold Bar struvite at pH 8.

5.5.3.2 Total magnesium concentration versus time at pH 9

The magnesium concentration profile at pH 9 showed smaller increases over time because the solubility of heated struvite is lower at higher pH (Figure 29). Magnesium is

not released from the pellets in large quantities like at pH 8. The percent increase in magnesium from solution ranged from -90 to 110%. This means that, in some experiments, magnesium was taken out of solution rather than being dissolved from the pellet source. These results correspond to the generally lower ammonium removals at pH 9, because of the smaller supply of available magnesium to form struvite.

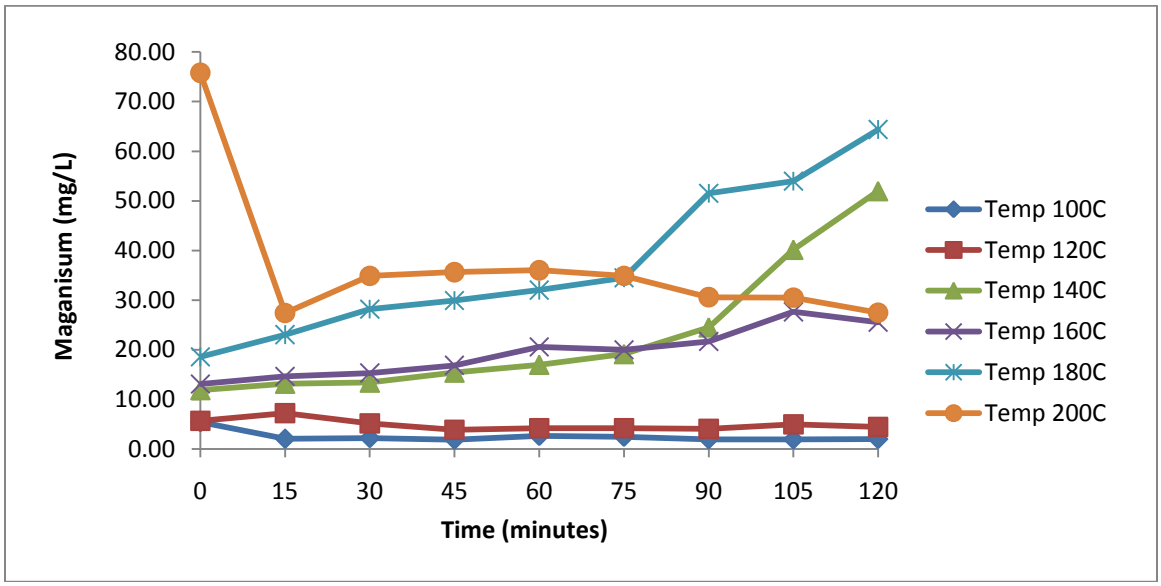

Figure 29 Magnesium concentration for Gold Bar struvite at pH 9.

5.5.3.3 Total magnesium concentration versus time at pH 10

Heated struvite pellets are most stable in the pH 10 solution. Magnesium release was minimal, ranging from -90 to 40% (Figure 30). Again, in some experiments, magnesium was taken out of solution rather than being added to solution from the pellet source. Since magnesium is not released in high quantities during pH 10 experiments, it makes sense that the least ammonium removals also occurred during the pH 10 experiments (Figure 24) as compared to the pH 8 experiments (Figure 22).

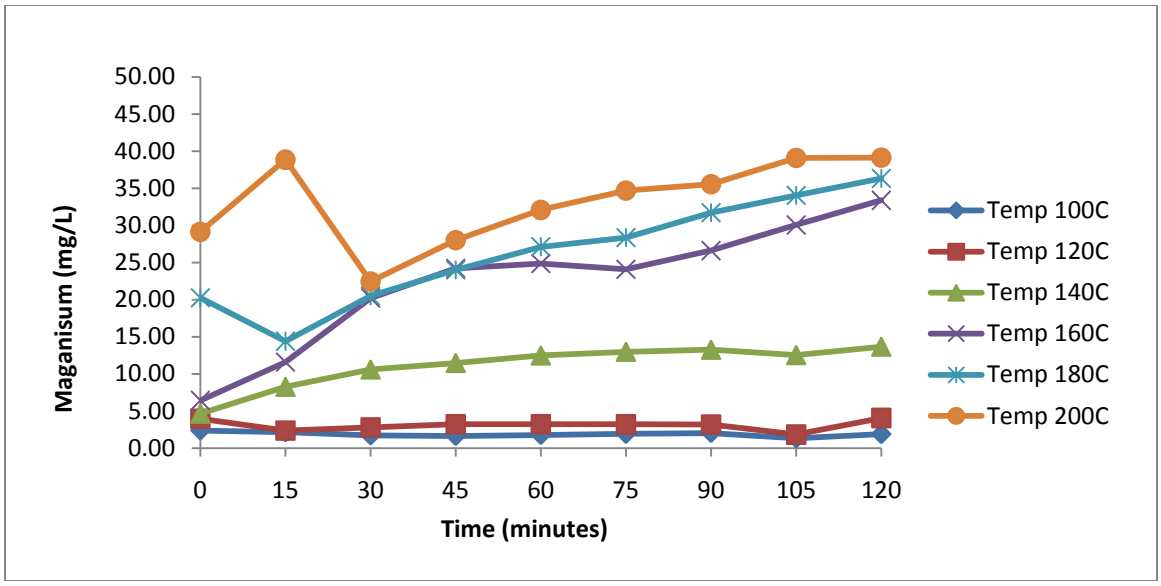

Figure 30 Magnesium concentration for Gold Bar struvite at pH 10.

5.5.3.4 Total magnesium removal summary

Lower pH causes heated struvite to become a source of magnesium in solution. This affect is amplified if the pellets were heated at temperatures 140°C and above. Below 140°C, the pellets are likely not dehydrated enough to allow for "melting." Thus, a trade off also exists between ammonium removal and magnesium release. Ammonium cannot be effectively removed from solution without the pellets acting as a source of magnesium back to solution.

5.5.4 Solution supersaturation ratio (SSR)

The SSR was calculated for each sample taken every 15 minutes using the Potts model. The variables measured were magnesium, phosphate, and ammonium concentrations, as well as temperature and conductivity. SSR is a measure of how much natural drive towards struvite crystallization exists in solution at any moment.

5.5.4.1 SSR at pH 8

The supersaturation ratios for experiments at pH 8 are shown in Figure 31. The four highest temperatures showed an initial increase in SSR followed by a subsequent decrease. This suggests that heated struvite dissolves at pH 8, releasing magnesium and phosphate into solution. This large molar source of magnesium and phosphate is likely the reason why ammonium reduction is so effective at pH 8. The two lowest temperatures do not show the same spike in SSR. This is likely because magnesium is not released from the pellets as shown in Figure 28, resulting is less ammonium removal. The SSR declined to a value below five, as the time reaches 120 minutes, suggesting that the struvite reaction is essentially complete.

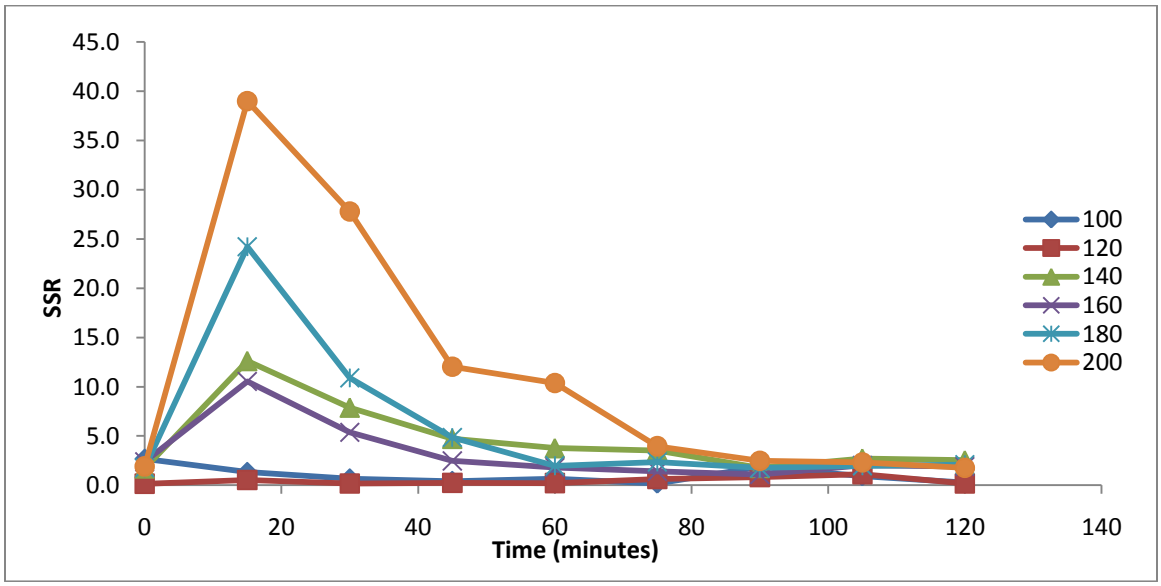

Figure 31 SSR vs. time for various temperatures at pH 8.

5.5.4.2 SSR at pH 9

The SSR for experiments conducted at pH 9 is shown in Figure 32. Initially the SSR was high for all experiments, but then decreases over time. The SSR values are higher than for the corresponding experiments at pH 8. This means that more ions remain in solution

at pH 9. This is counter-intuitive, considering the previous argument that heated struvite is more soluble at lower pH values. Much more magnesium and phosphate are released back into solution at pH 8, compared to at pH 9. These ions quickly react with available ammonium to form struvite. This leaves excess magnesium and phosphate in solution but not ammonium, which leads to the decline in SSR. On the other hand, magnesium and phosphate are released more slowly and in smaller quantities at pH 9. Also, the releases are not necessarily stoiciometrically favourable for the formation of struvite and thus ammonium is removed less effectively from solution. Since all three components exist in solution in varying amounts, the SSR remains at a moderate level (SSR>10) for the majority of the experiments.

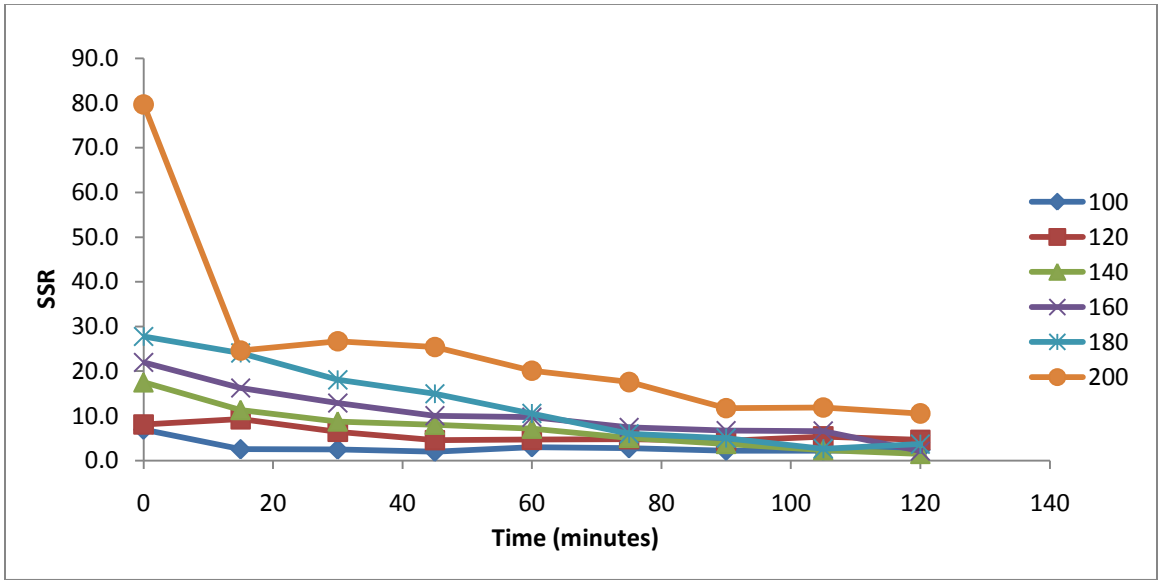

Figure 32 SSR vs. time for various temperatures at pH 9.

5.5.4.3 SSR at pH 10

The SSR for experiments conducted at pH 10 is shown in Figure 33. Here, the SSR values remain relatively large throughout the duration of all experiments. Heated struvite is even less soluble at pH 10, and not enough magnesium dissolves into solution to make

the formation of struvite as favourable as compared to pH 8. There is a large concentration of ammonium and phosphate that don't have enough magnesium to form struvite, but still result in a relatively high SSR. Another possibility is that magnesium is released into solution in sufficient concentrations but is converted to an unavailable form of magnesium that is less reactive with ammonium and phosphate such as $MgOH^+$, or $Mg(OH)_2$.

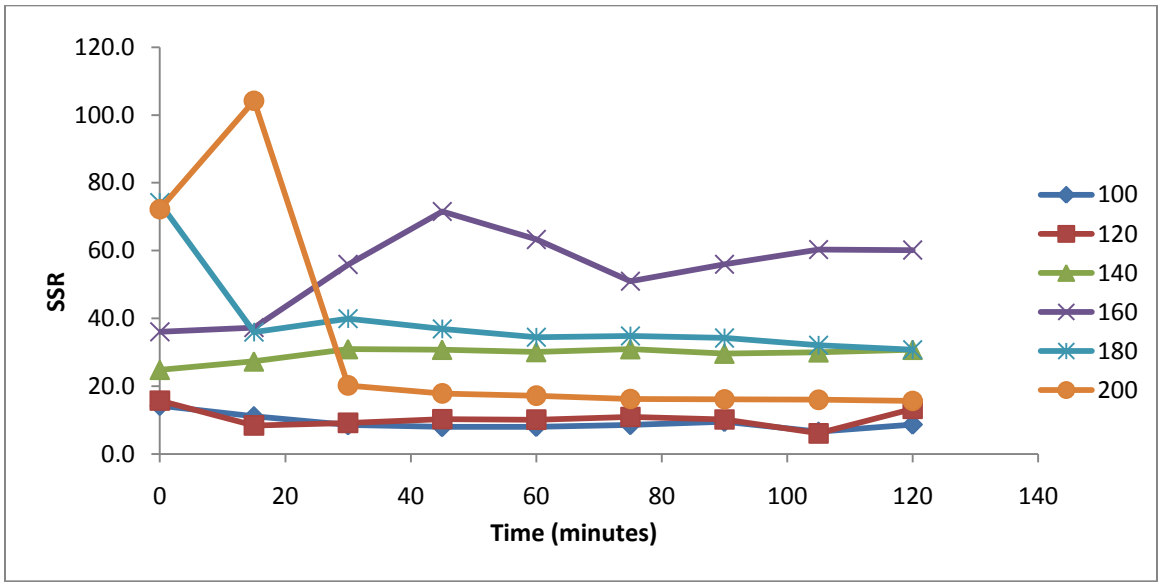

Figure 33 SSR vs. time for various temperatures at pH 10.

5.5.5 Struvite fines production (dissolution-reformation validation)

To quantitatively understand how well a heated pellet acts as a source of magnesium and phosphate, the fines were separated, dried on the lab bench, and weighed after the uptake reaction was completed. The samples at pH 8 produced a larger percentage of fines by weight, compared to pH 9 and pH 10 (Figure 34). The large release of phosphate (Figure 25) and magnesium (Figure 28) effectively removes ammonium from solution (Figure 22). The large SSR ratios at the beginning of the reaction confirms the large increase in phosphate and magnesium and also explains how 2-15% new fines (by total mass) are

formed, despite the feed solution being undersaturated with respect to struvite. The chemical identity of the fines is discussed in subsequent sections. It appears as though the trade off between ammonium removal and magnesium and phosphate release is validated. The unfortunate by product of ammonia removal, using heated struvite pellets, is a large percentage of fines formation. These fines are unwanted because they may clog up the struvite crystallizer. From an economical/marketing perspective, it is unsuitable to dissolve a valuable fertilizer pellet only to reform the same fertilizer, but in the form of a fine dust. However, for the purposes of ammonia removal alone, this may become a useful process.

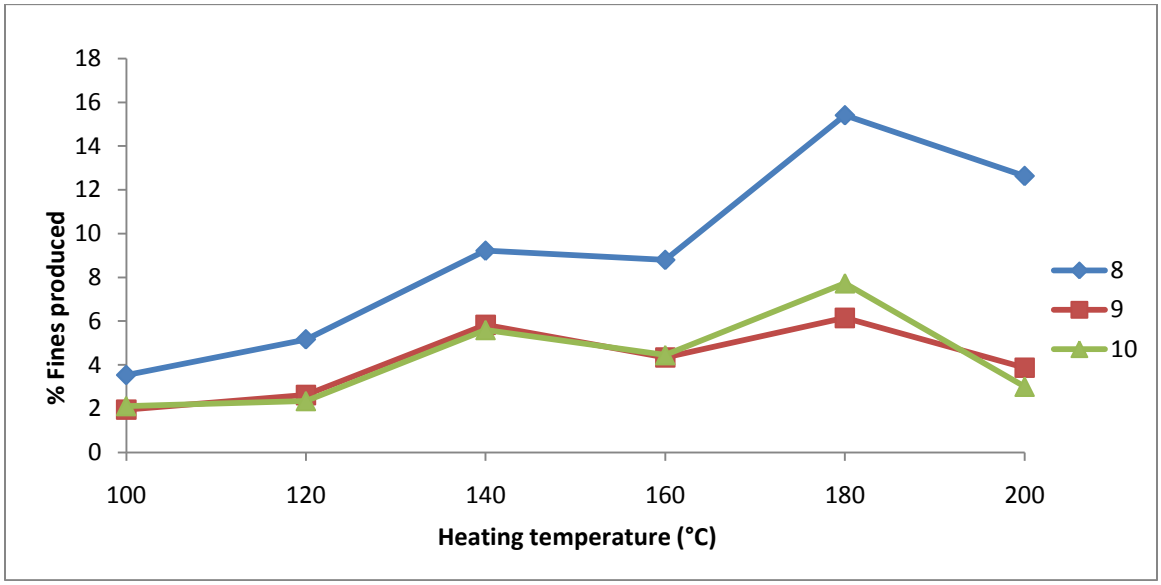

Figure 34 Percent fines produced versus isothermal heating temperature for pH 8, 9, and 10.

5.5.6 Caustic usage

The amount of caustic used over time is shown for each temperature experiment over the three pH values (Figure35-37). It is seen that the amount of caustic use at the beginning is largest and minimal after the first 15 minutes. This is likely because most of the ammonia is removed from solution in the first 15 minutes. The pellet dissolves and becomes a

source of magnesium and phosphate and subsequently forms new struvite fines; this reduces the pH and requires an addition of caustic to maintain the pH set point.

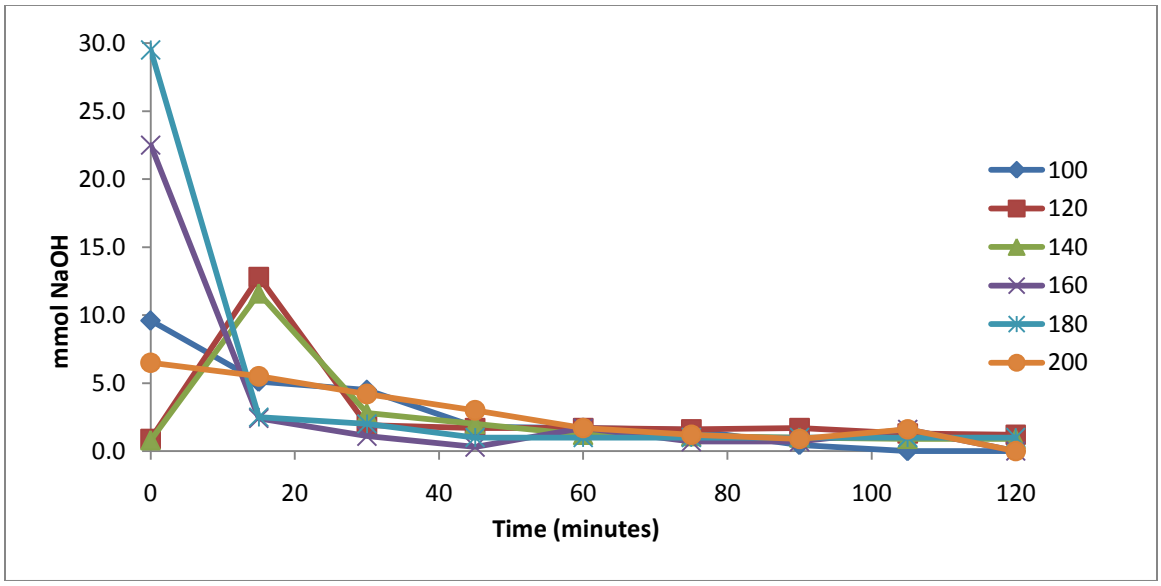

Figure 35 Volume NaOH used vs. time for pH 8.

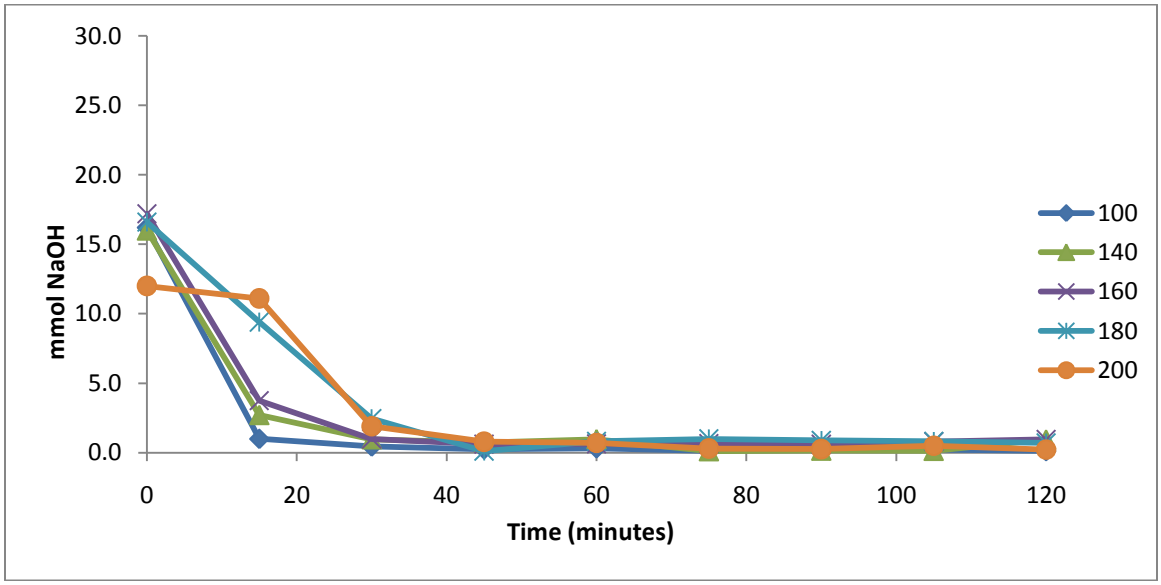

Figure 36 Volume NaOH used vs. time for pH 9.

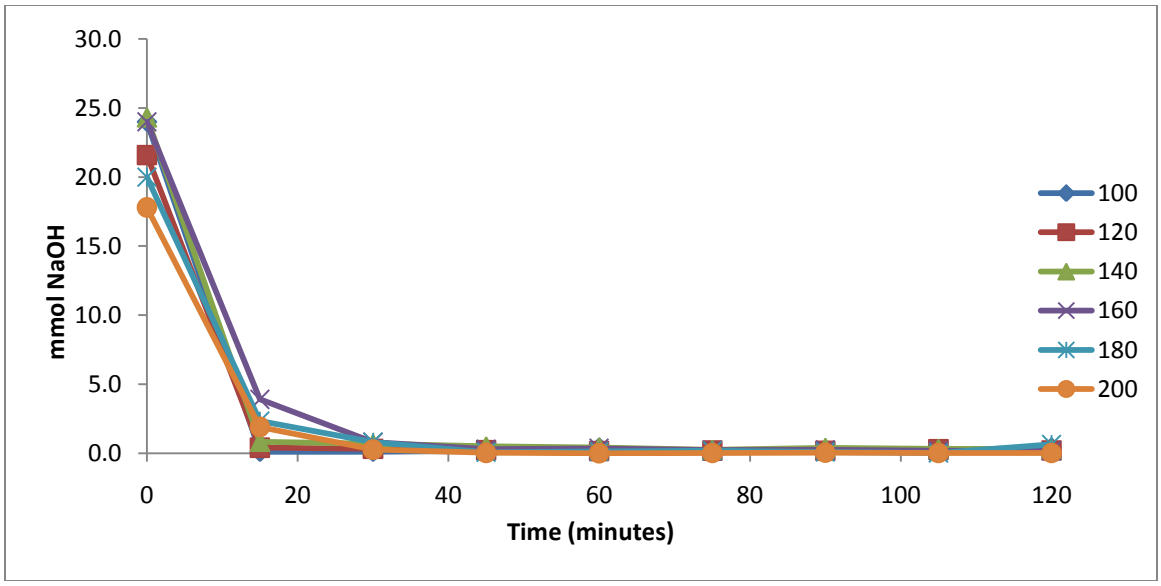

Figure 37 Volume NaOH used vs. time for pH 10.

The total caustic use was recorded for each two hour ammonium removal experiment (Figure 38). Considering that the heated struvite is more soluble at lower pH and for pellets isothermally heated at higher temperatures, the caustic usage should be maximized. There is no clear trend in caustic usage. This is likely due to experimental error. Sometimes, caustic was added in quantities leading to a pH higher than the desired set point. Also, the volume added was determined by eye. A more rigorous record of caustic use is likely to result in an increase in caustic use at lower pH conditions, since heated struvite becomes a source of magnesium and phosphate which can react to form new struvite. When struvite forms, the pH is lowered, requiring an addition of caustic to maintain constant pH.

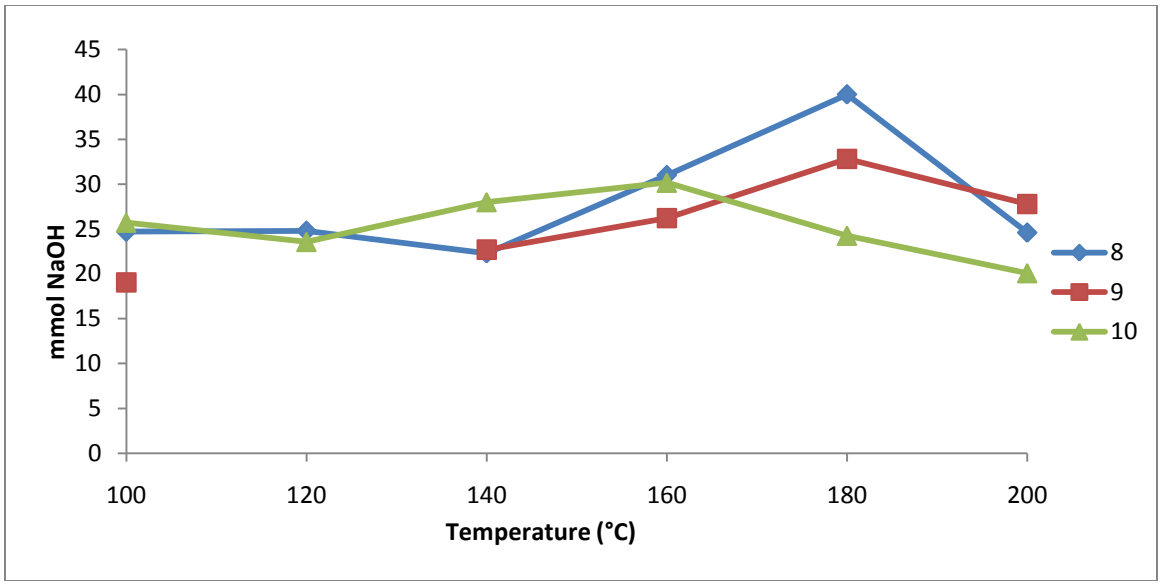

Figure 38 Total mmol NaOH used versus temperature for 3 pH values.

5.5.7 Molar ratio comparison across solid products

Heated struvite, uptake struvite, and fine struvite samples were dissolved in water and acid, and their contents analyzed. The three molar ratios were calculated for each of the heating temperature-pH experimental combinations. The purpose was to semi-quantitatively determine the conditions producing the best ammonium removal.

5.5.7.1 N:P ratio comparison of roasted versus uptake versus fine struvite

The N:P ratios calculated for each pH and heating temperature condition are shown in Figure 39-41. In general, the N:P ratio of roasted struvite declined with increasing temperature, as more ammonia is released from the crystal. Also, the N:P ratio increased slightly for most samples of uptake struvite compared to roasted struvite. This suggests that a fractional amount of ammonium is taken from solution and recovered into the pellet. The new fines formed possessed an N:P ratio that is closer to the characteristic

struvite ratio of 1:1. This suggests that fines formed are likely to be struvite, whereas uptake pellets are a mixture of magnesium phosphates, and possibly a thin struvite cover.

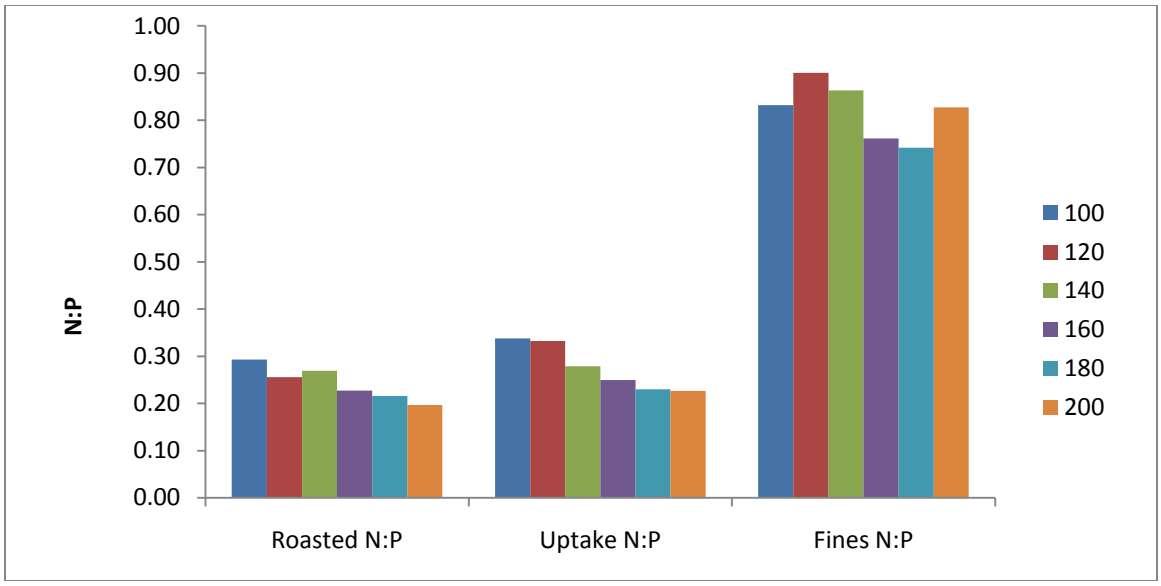

Figure 39 N:P ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 8.

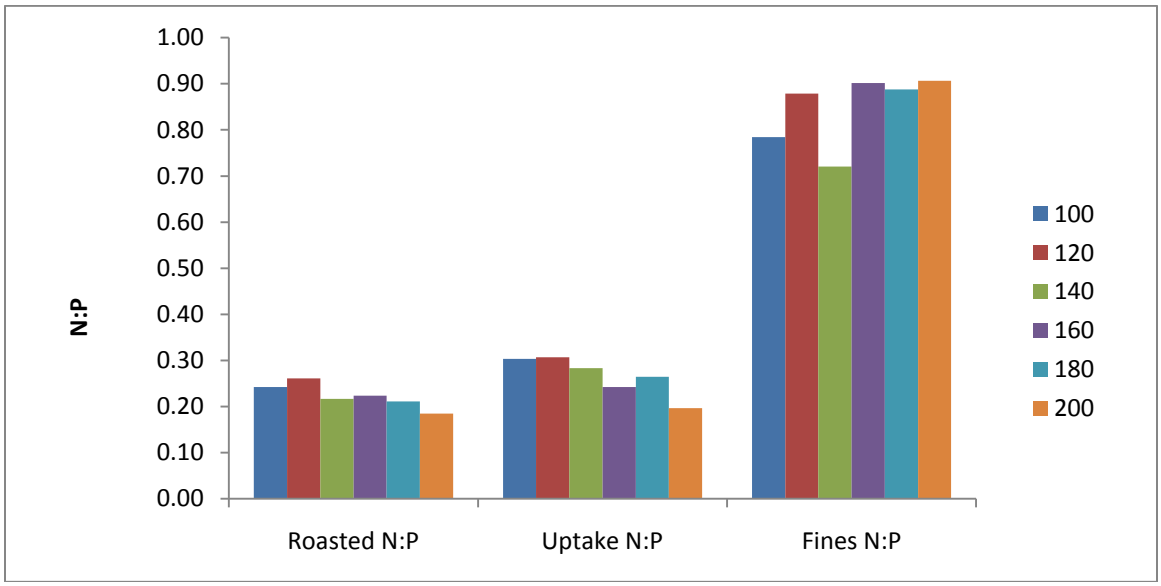

Figure 40 N:P ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 9.

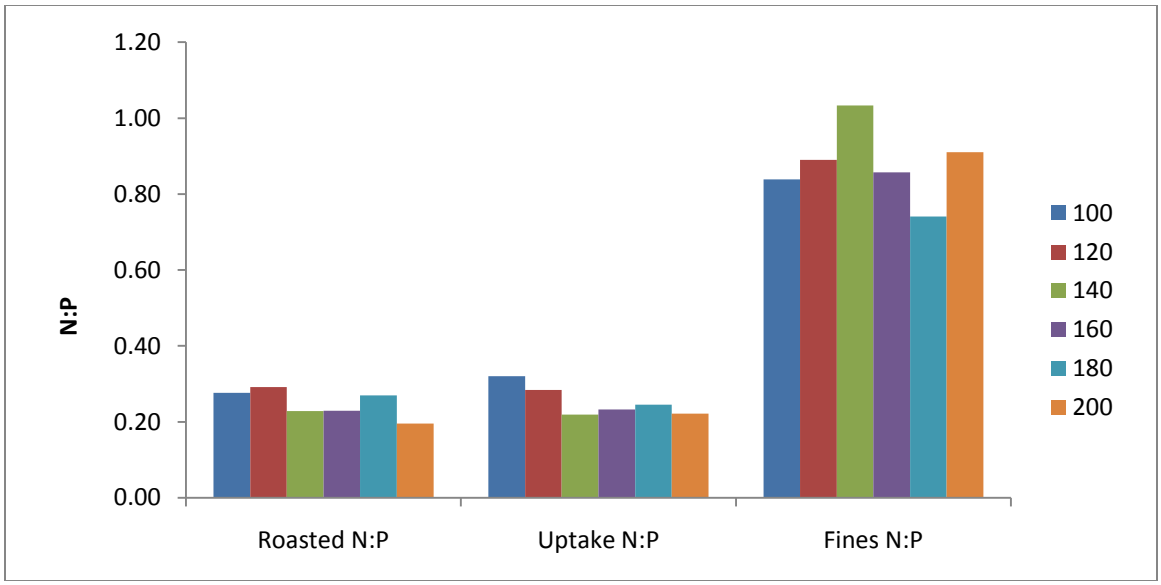

Figure 41 N:P ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 10.

5.5.7.2 N:Mg ratio comparison of roasted versus uptake versus fine struvite

The N:Mg ratios calculated for each pH and heating temperature condition are shown in Figure 42-44. Similar trends to the N:P ratios are found because the nitrogen is compared to magnesium instead of phosphate, both of which are non-volatile.

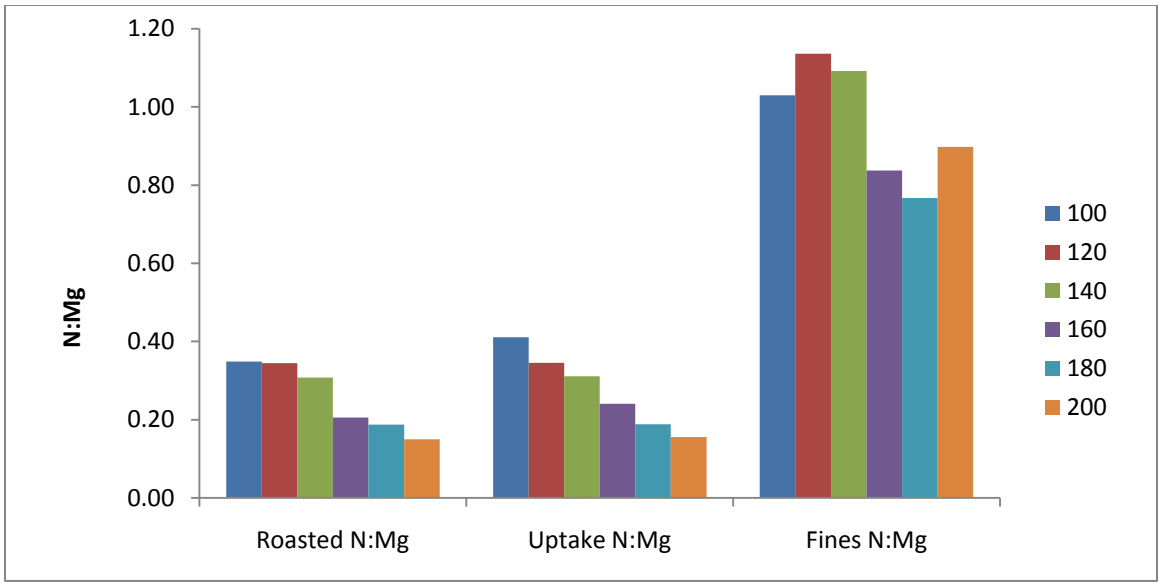

Figure 42 N:Mg ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 8.

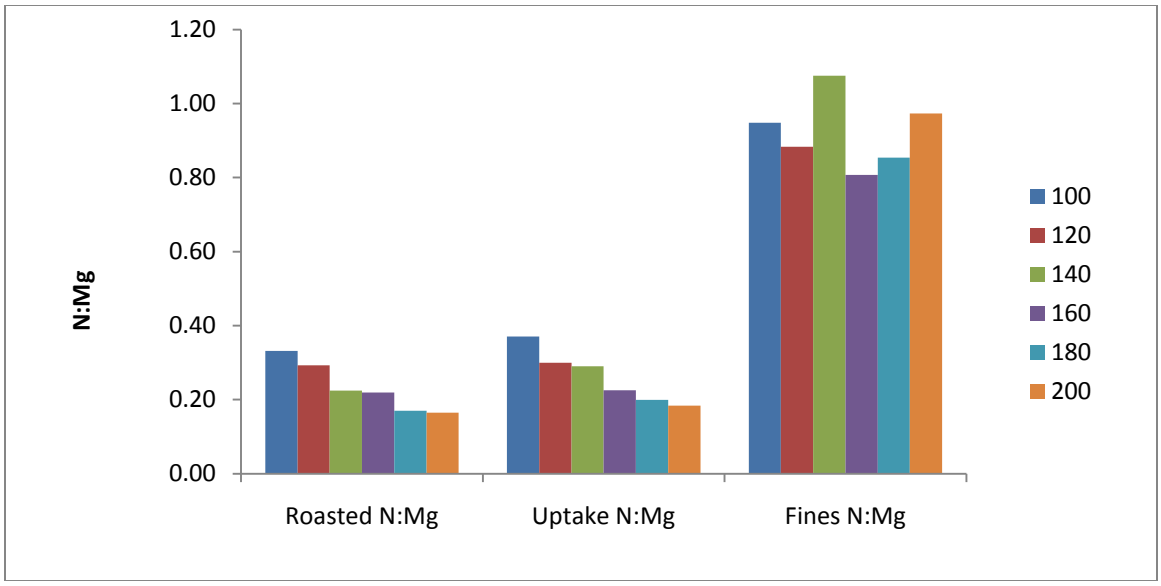

Figure 43 N:Mg ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 9.

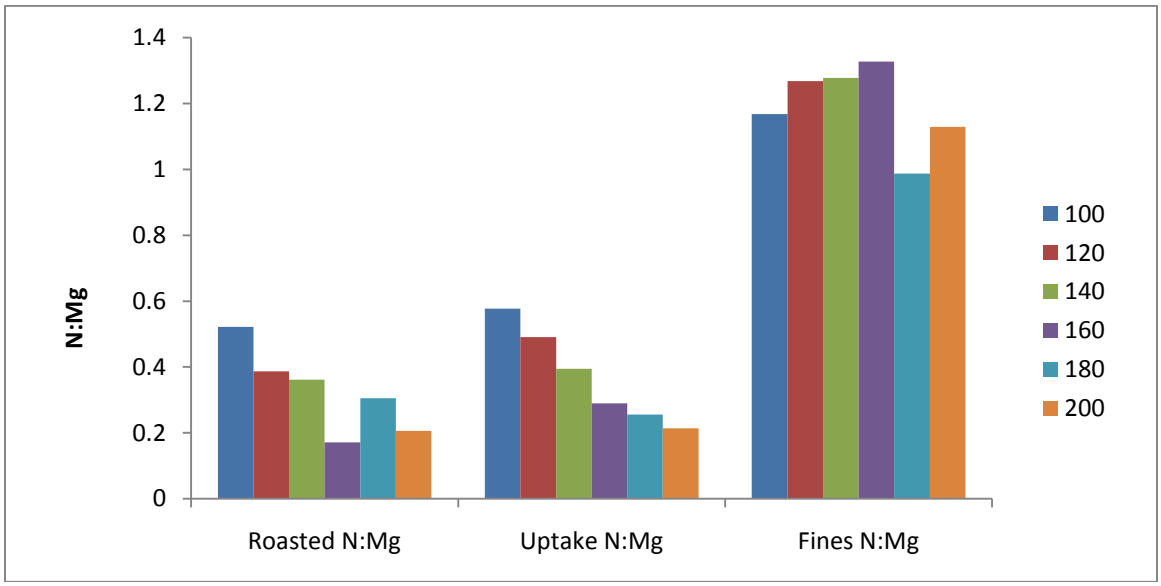

Figure 44 N:Mg ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 10.

5.5.7.3 Mg:P ratio comparison of roasted versus uptake versus fine struvite

The Mg:P ratios calculated for each pH and heating temperature condition are shown in Figure 45-47. Both magnesium and phosphorus are non-volatile at the heating temperatures applied during these experiments. It was expected that ratios for all experimental combinations would be close to the ideal 1:1. The ideal ratio was found to

be true, for fine struvite at all temperatures and pH conditions. However, an unexpected observation occurred for the heated and uptake samples. There was an upward trend towards an increasing Mg:P ratio with increasing heating temperature. This result confirms the more quantitative elemental analyses whose Mg:P ratios were 1.2 and1.5 for 160°C and 200°C, respectively (Figure 14).

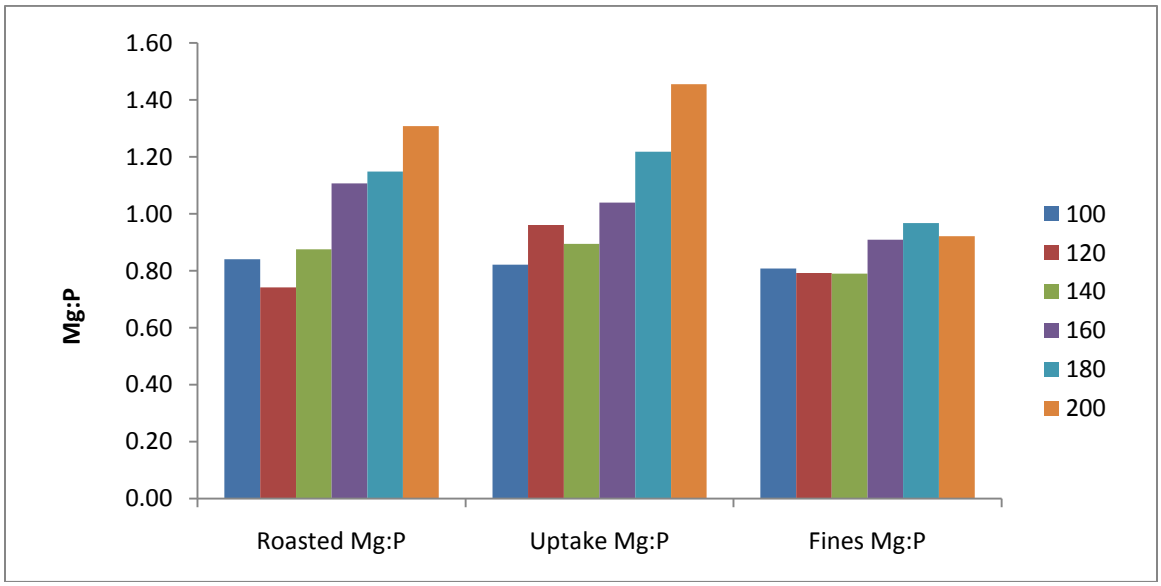

Figure 45 Mg:P ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 8.

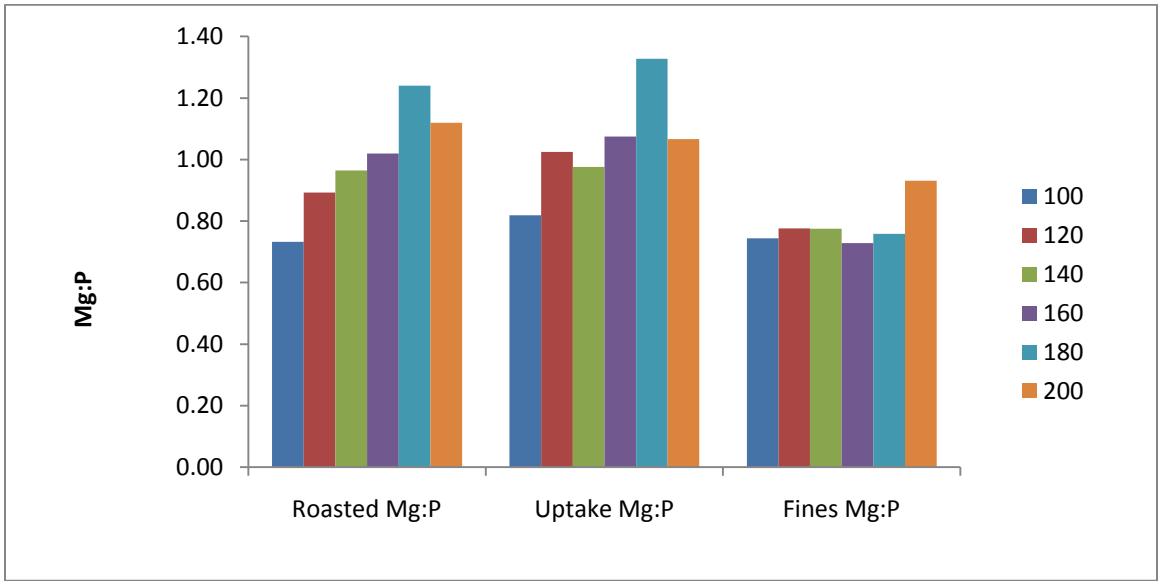

Figure 46 Mg:P ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 9.

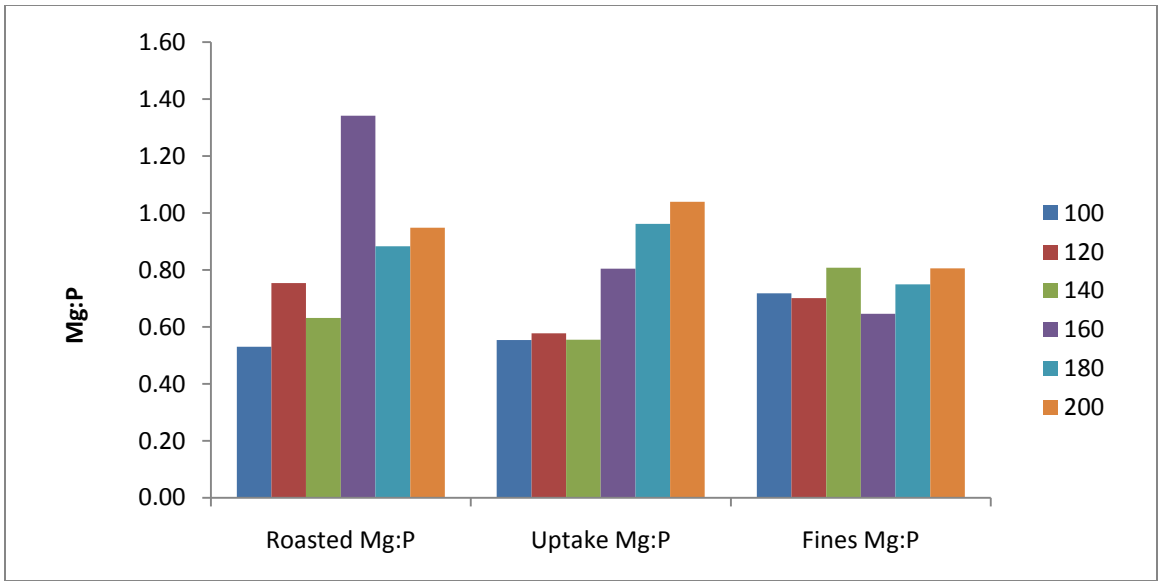

Figure 47 Mg:P ratios for roasted, uptake, and fine struvite. Six different roasting temperatures were used and all uptake experiments were conducted at pH 10.

5.5.8 Effect of temperature on molar ratios

The temperature that pellets were roasted at was hypothesized to influence the molar ratios of the three solid products. The results were compared across three pH values.

5.5.8.1 Molar ratios versus temperature for constant pH 8

At constant pH 8 it was observed that both the roasted and uptake pellets exhibit a decrease in N:P and N:Mg ratio with increasing temperature (Figure 48-Figure 49). The fines have N:P and N:Mg ratios of about 1:1 indicating pure struvite. The Mg:P ratio in the fines is also indicative of struvite (Figure 50). However, the Mg:P ratio of the roasted and uptake pellets increases past unity above a heating temperature of 140°C. This result agrees with results from elemental analysis (Figure 14).

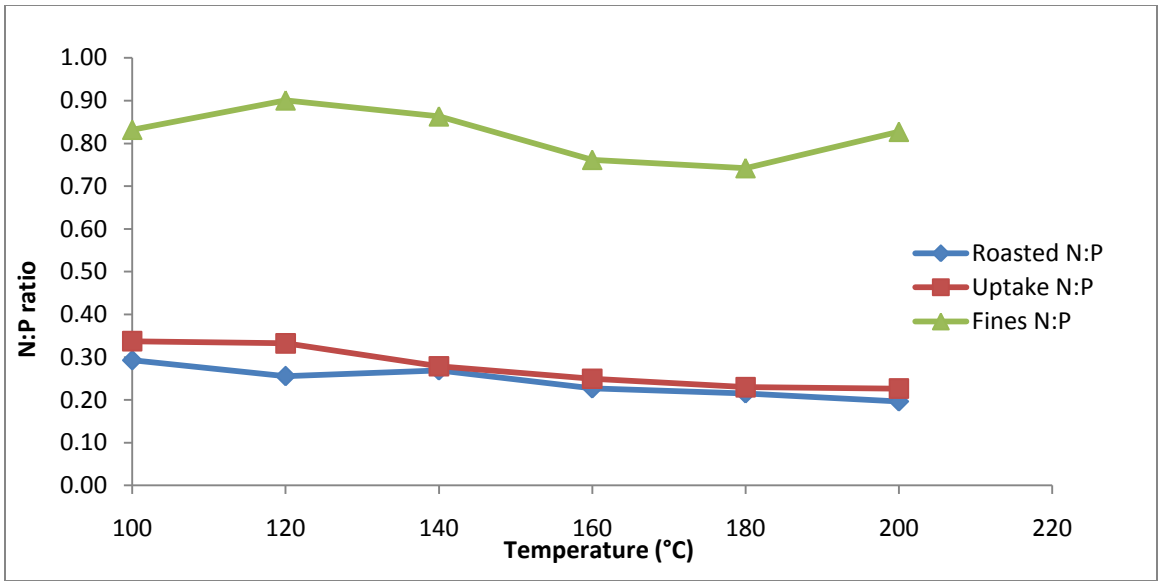

Figure 48 N:P ratios versus temperature for pH 8.

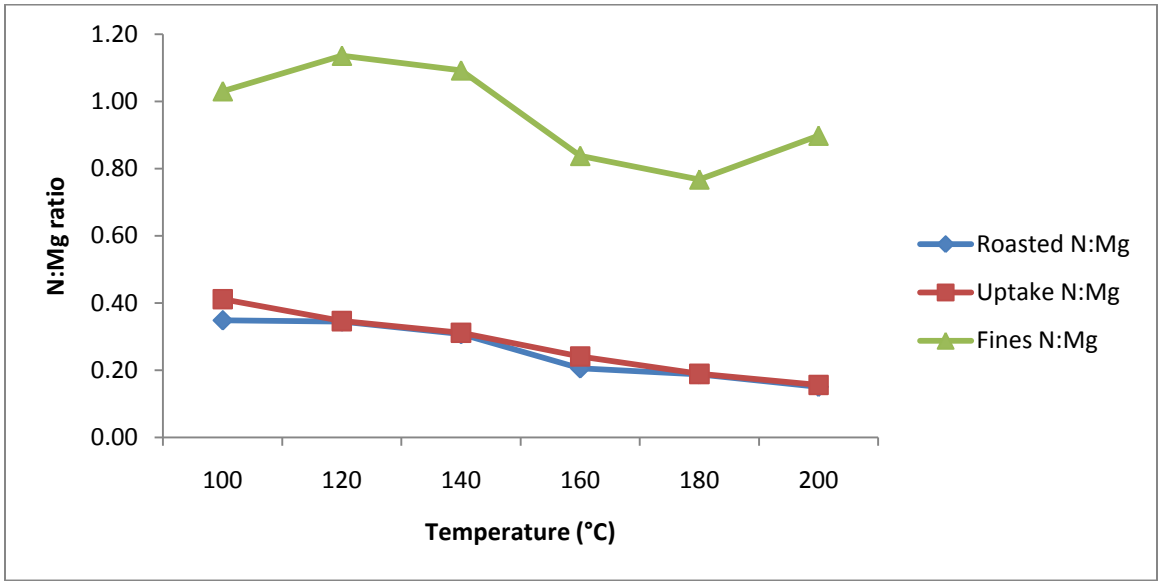

Figure 49 N:Mg ratios versus temperature for pH 8.

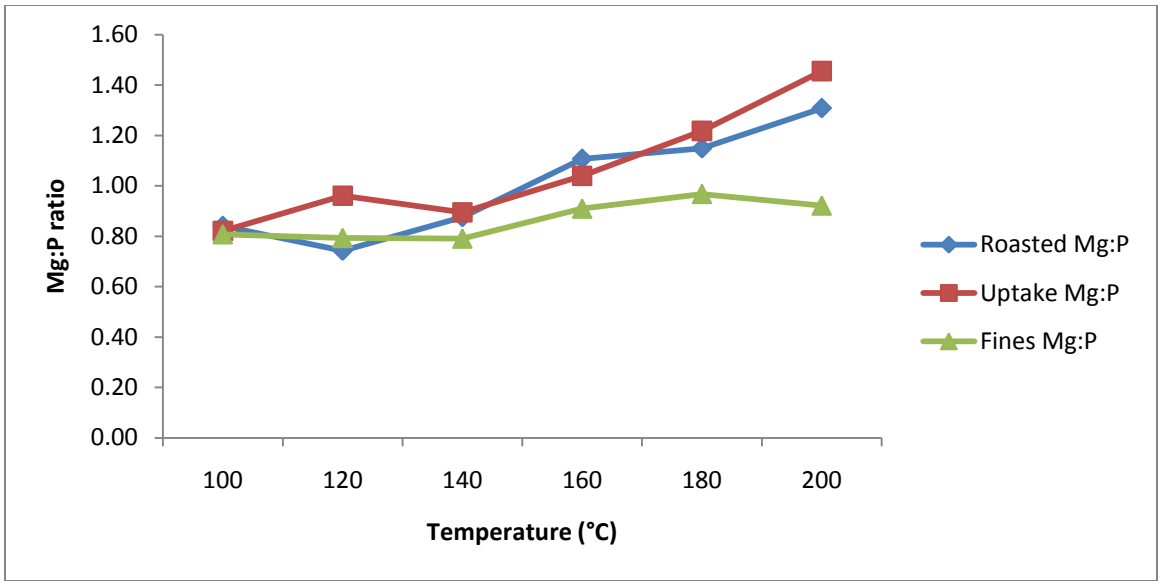

Figure 50 Mg:P ratios versus temperature for pH 8.

5.5.8.2 Molar ratios versus temperature for constant pH 9

Similar to pH 8, the N:P and N:Mg ratios of roasted and uptake struvite decline with increasing roasting temperature, and whereas the ratio in the fines is indicative of struvite (Figure 51-52). Again, the Mg:P ratio of roasted and uptake struvite becomes greater than unity at heating temperatures greater than 140°C (Figure 53).

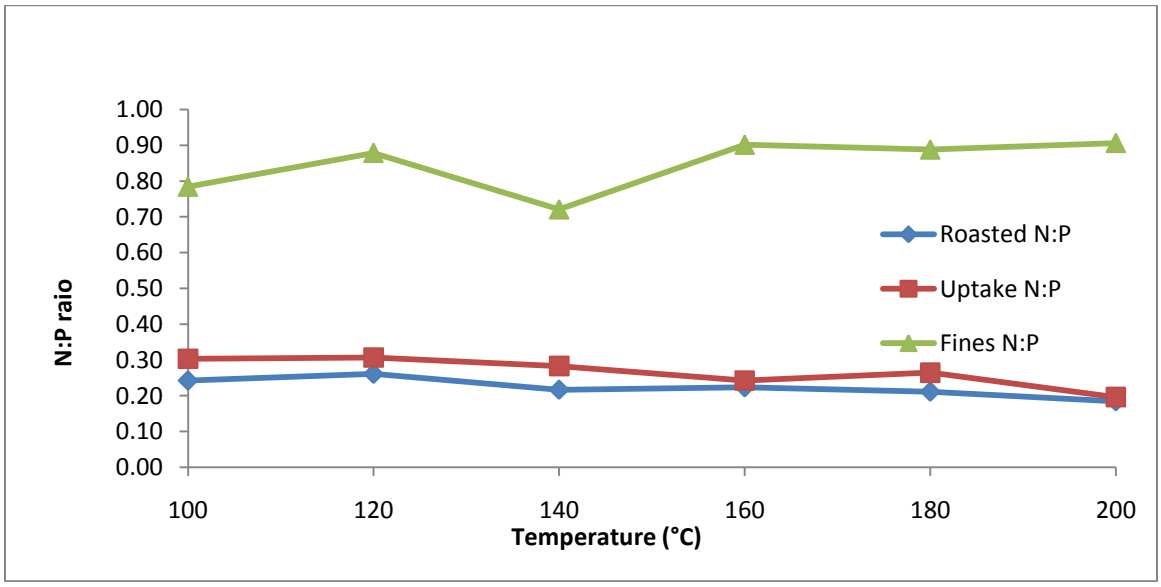

Figure 51 N:P ratios versus temperature for pH 9.

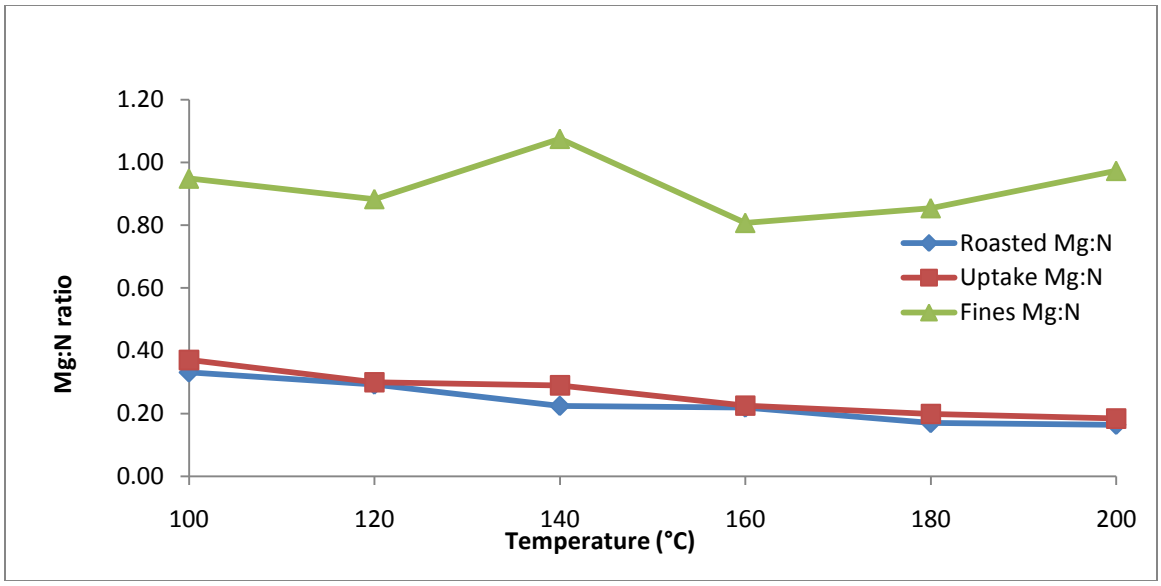

Figure 52 N:Mg ratios versus temperature for pH 9.

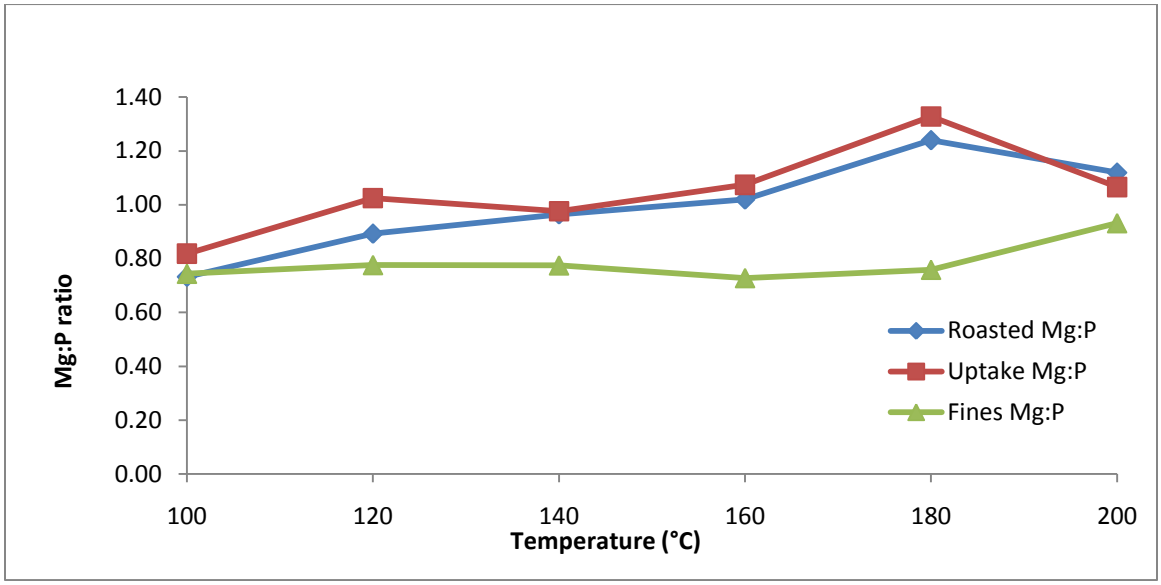

Figure 53 Mg:P ratios versus temperature for pH 9.

5.5.8.3 Molar ratios versus temperature for constant pH 10

Similar to pH 8 and 9, the N:P and N:Mg ratios of roasted and uptake struvite decline with increasing roasting temperature, and whereas the ratio in the fines is indicative of struvite (Figure 54-55). The Mg:P ratio of roasted and uptake struvite becomes does not

become greater than unity at heating temperatures greater than 140°C but still exhibits an increasing trend (Figure 56).

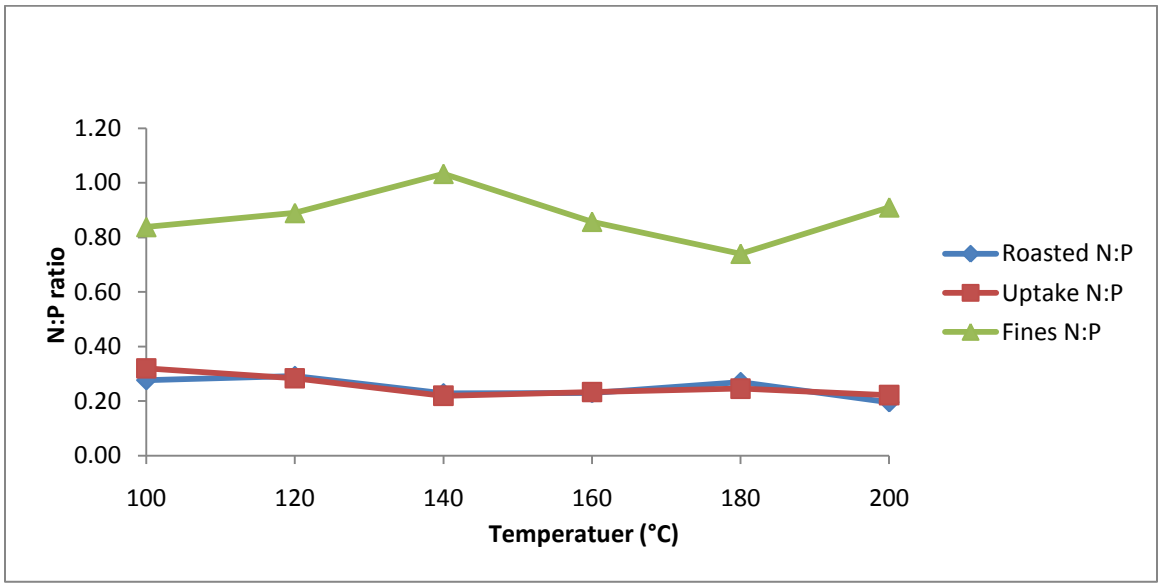

Figure 54 N:P ratios versus temperature for pH 10.

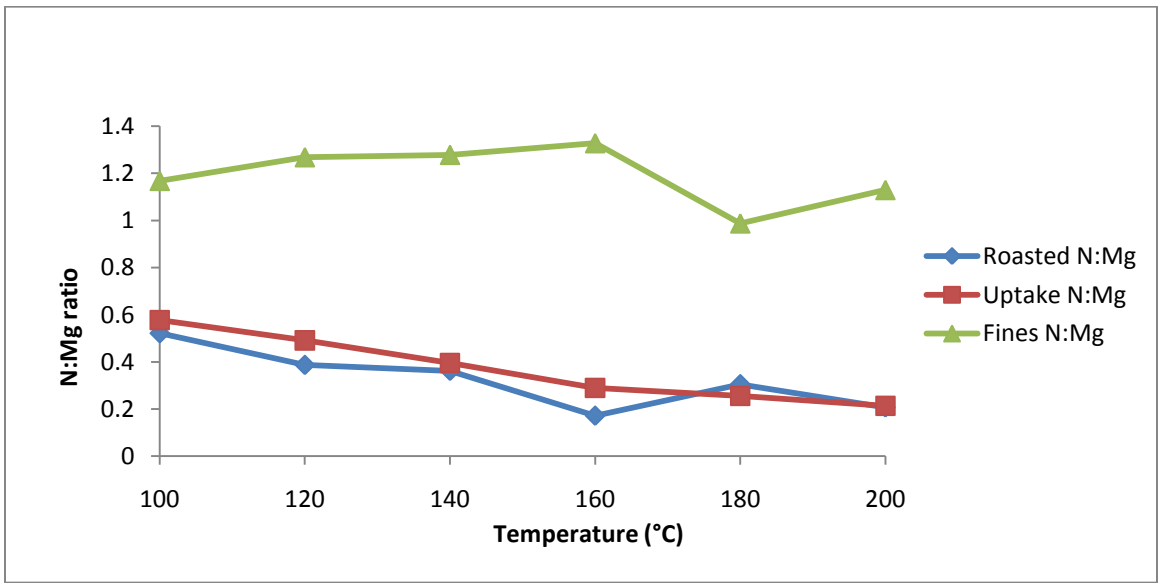

Figure 55 N:Mg ratios versus temperature for pH 10.

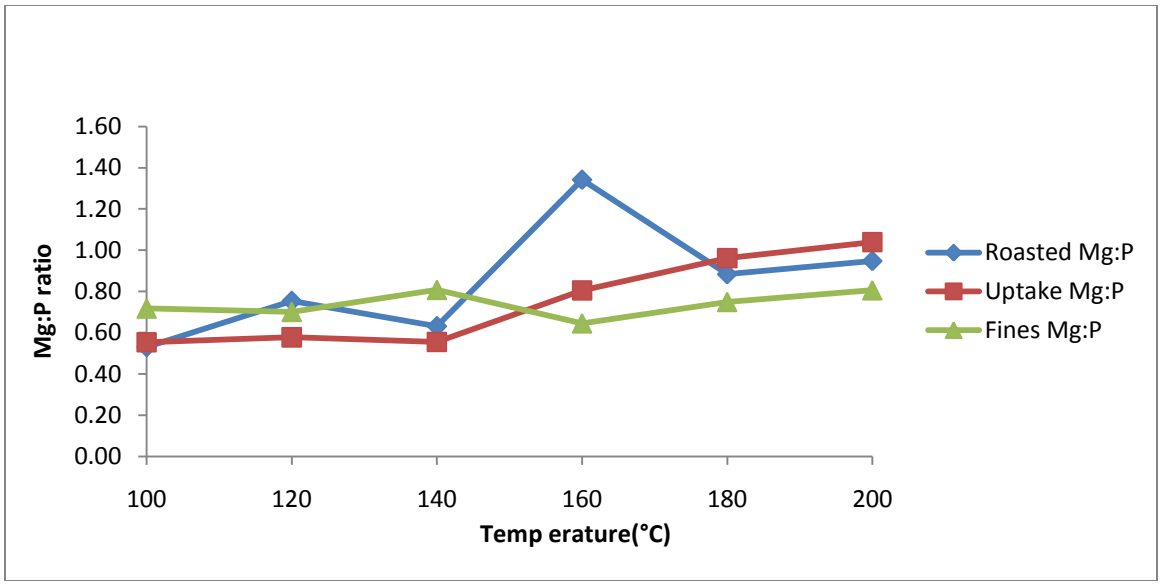

Figure 56 Mg:P ratios versus temperature for pH 10.

5.5.9 Effect of pH on molar ratios for constant temperatures

The pH of the uptake reaction was hypothesized to influence the effectiveness of the desired uptake reaction. Molar ratios of the three solid products versus pH were calculated. For all six temperatures, the uptake N:Mg increases when the reaction takes place at pH 10 instead of pH 8 or 9 (Figure 57-Figure 62). However, the uptake N:P ratio does not have this same trend. This can be rationalized by the decrease in Mg:P ratio of both the roasted and uptake struvite when the reaction takes place at pH 10 instead of pH 8 or 9. Essentially, these results suggest that divalent magnesium ion becomes unavailable at higher pH values due to conversion into magnesium hydroxide species.

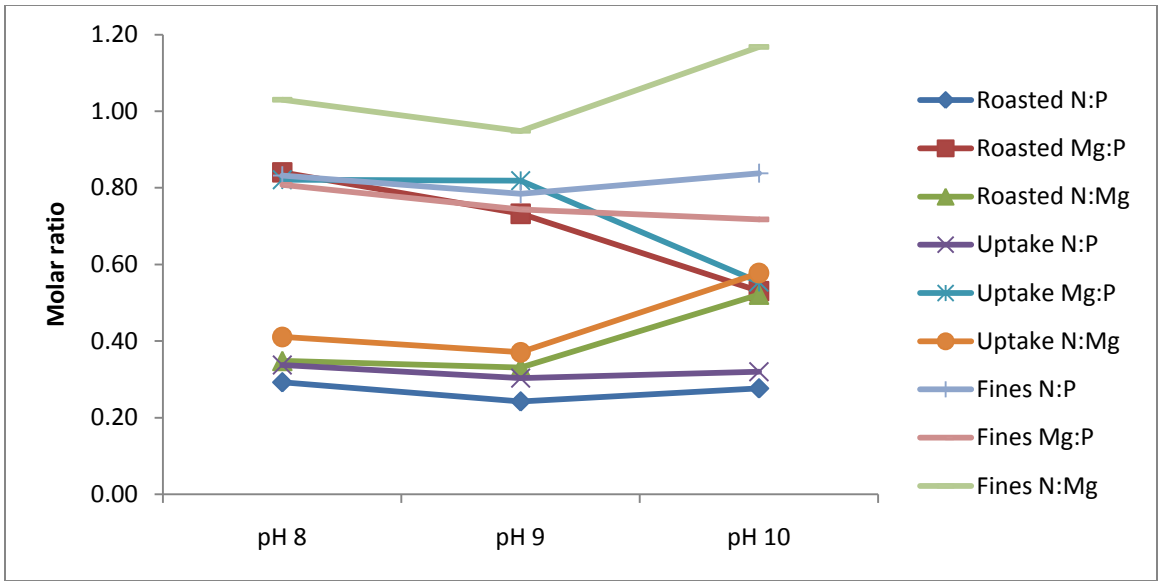

Figure 57 Solid product molar ratios vs. pH for a heating temperature of 100°C.

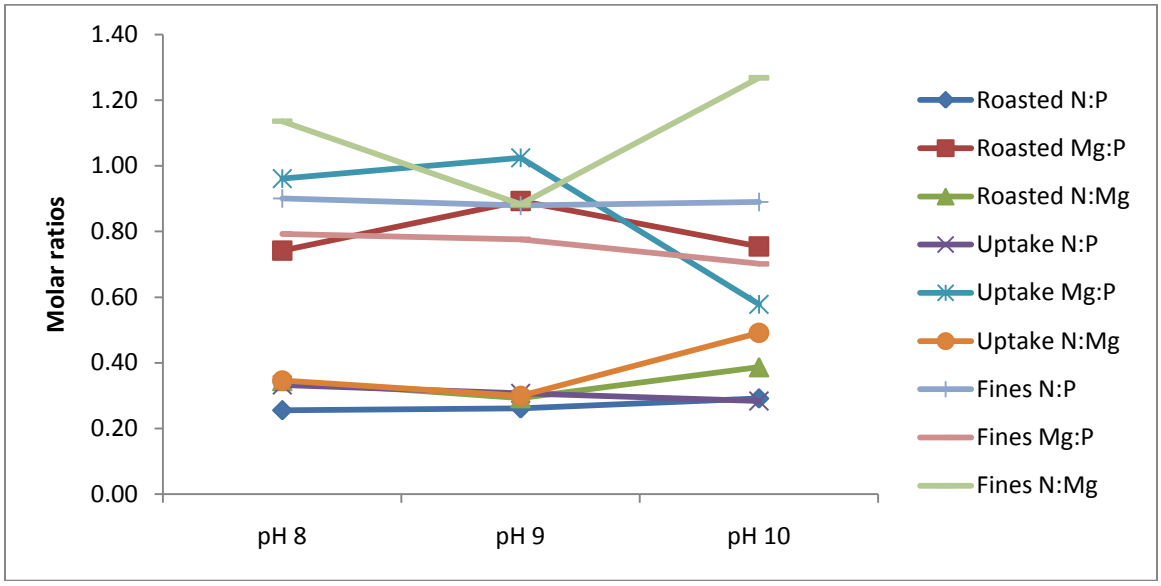

Figure 58 Solid product molar ratios vs. pH for a heating temperature of 120°C.

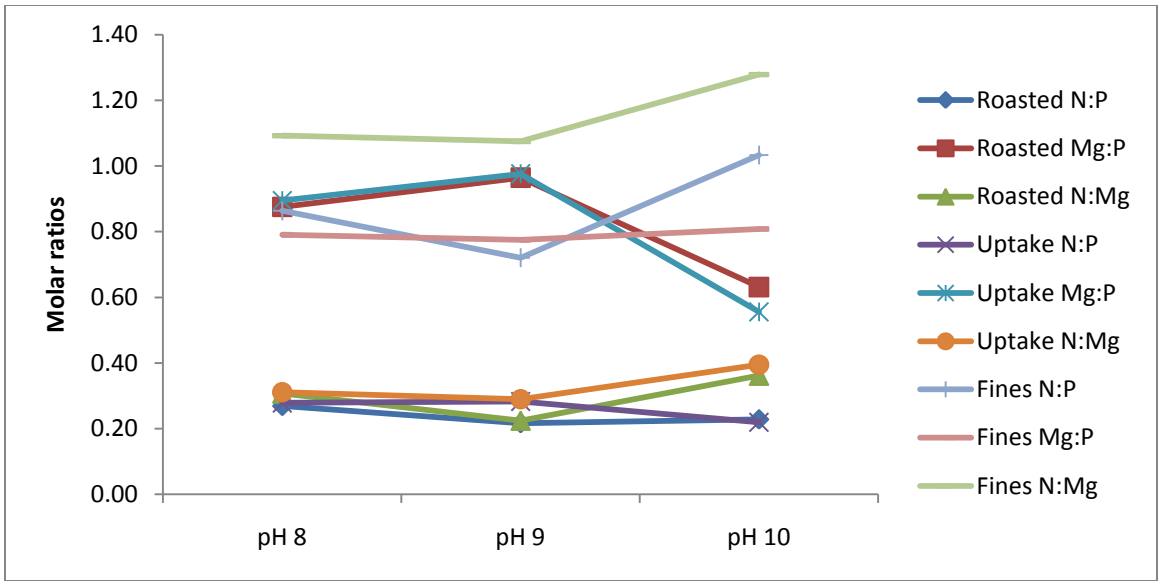

Figure 59 Solid product molar ratios vs. pH for a heating temperature of 140°C.

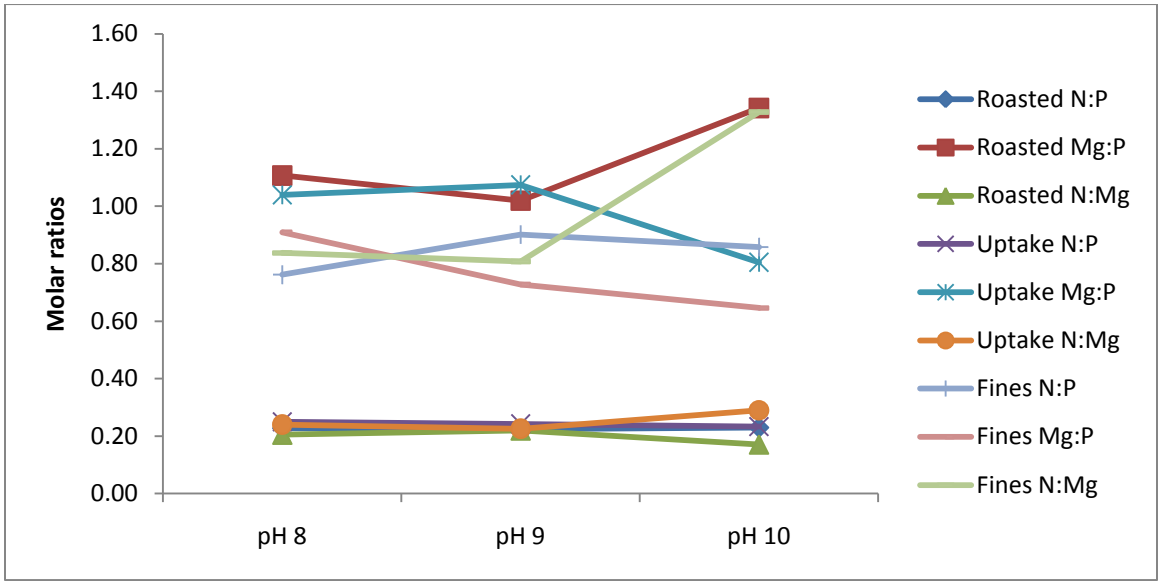

Figure 60 Solid product molar ratios vs. pH for a heating temperature of 160°C.

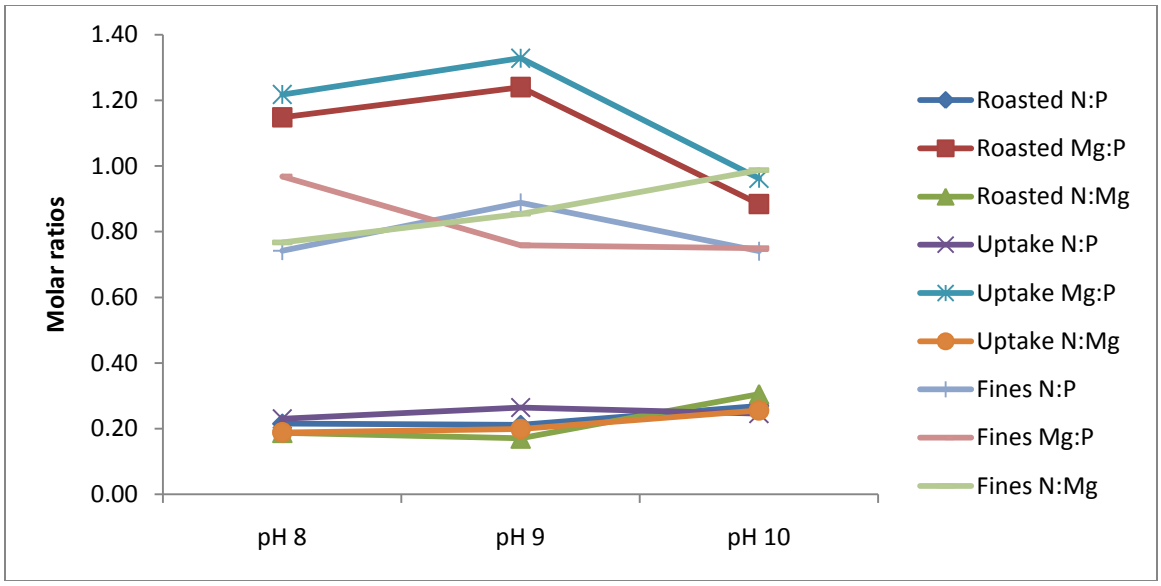

Figure 61 Solid product molar ratios vs. pH for a heating temperature of 180°C.

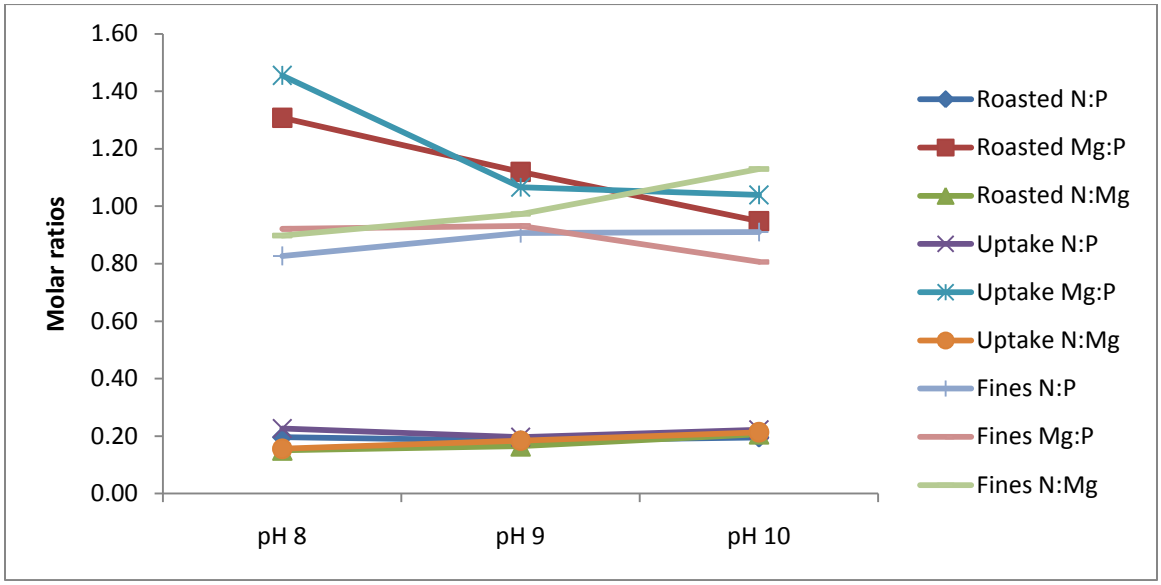

Figure 62 Solid product molar ratios vs. pH for a heating temperature of 200°C.

5.5.10 Mass balance

Mass balance calculations were conducted to quantitatively determine the sources, transfers, and sinks for the three species in struvite: Mg^{2+}, NH_4^+, and PO_4^{3-}. The masses of "heated struvite" were recorded before the uptake reaction. Struvite that remained on the 1mm, 500µm, and 250µm sieves were summed together and labelled as "total uptake

struvite". Struvite that passed through the 250μm sieve was summed with struvite that remained on the filter paper and was labelled as "total fine struvite". Mass balance data spreadsheets can be found in Appendix B.

5.5.10.1 N balance

Bar graphs and a summary table illustrating the nitrogen balances for each experimental condition can be found in Appendix D. In most experiments, a nitrogen mass "imbalance" occurred. Nitrogen balance ranged from 88-181% of initial nitrogen. More nitrogen was calculated to be in the fines and uptake pellets than was available (ie. the mass of nitrogen removed from solution). This is likely due to experimental error. Care must be taken to control the water content in the particular components. The mass calculations are based on converting a solution concentration into a mass. The total mass of heated pellets was only recorded initially after being taken out of the oven, but not when the sub sample from these pellets were dissolved for analysis. During this time, atmospheric water absorbs onto a heated pellet, as shown in Figure 7, Figure 9, and Figure 11.

5.5.10.2 P balance

Bar graphs and a summary table illustrating the phosphorus balances for each experimental condition can be found in Appendix D. Phosphorus mass "imbalances" were calculated for most experiments; this was caused by the absorption of water on the heated pellets during the time between taken out of the oven and when the samples were actually analyzed. The imbalances ranged from 89-131% of initial phosphorus.

5.5.10.3 Mg balance

Bar graphs and a summary table illustrating the magnesium balances for each experimental condition can be found in Appendix D. Magnesium mass "imbalances" were also calculated for most experiments, ranging from 61-157%. The likely cause was also the absorption of water on the heated pellets during the time between taken out of the oven and when the samples were actually analyzed.

5.5.10.4 Summary of mass balance results

The mass "imbalances" are likely largely attributed to mass losses during transfer from the oven to the balance, and from the reactor to the weigh dish. Two other large sources of error include the fact that struvite is hygroscopic after heating, and the long duration (up to 5 days) needed for drying to an equilibrium temperature.

5.6 Uptake stage two: May 2010-August 2010

The second stage of struvite reformation experiments were conducted over a period of four months in 2010. Raw struvite from the Gold Bar WWTP was isothermally heated at three temperatures (80°C, 105°C, and 160°C) for 24 hours. Only three temperatures were selected at this stage, so that a comparison could be made between low, medium, and high temperature heating on ammonium removal. Also, only two different pH conditions were applied (pH 8 and pH 9) because it was concluded in Stage one that ammonium removal was unsatisfactory at pH 10. To obtain an estimate of the required amount of sorbent required, heated struvite was added in either 20g (40g/L) or 40g (80g/L) batches. The struvite reformation reactions were completed over a period of 2 hours, with aqueous samples being drawn from the reactor every 15 minutes.

5.6.1 Uptake experiments at constant pH 8

The three components of struvite were sampled every 15 minutes and stored for later analysis. The pH was maintained at constant pH 8 for the duration of uptake.

5.6.1.1 Total ammonia concentration versus time at constant pH 8

All experiments show decreasing ammonium concentrations versus time (Figure 63). In general, ammonium removal was better when the sorbent was heated at higher temperatures, and when sorbent addition was largest (Sugiyama et al., 2009). The best removal occurred for 40g sorbent heated to 160°C.

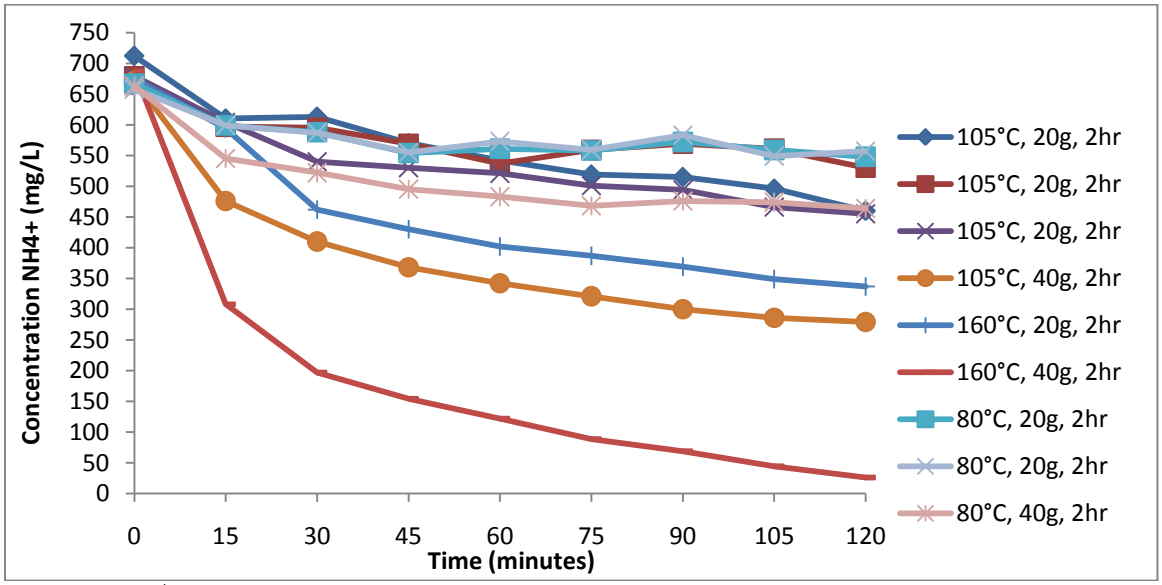

Figure 63 NH_4^+ concentration vs time at pH 8.

5.6.1.2 Ortho-phosphate concentration versus time at constant pH 8

All experiments show an increase in phosphate concentrations over time (Figure 64). The dissolution of phosphate from the pellets was higher for larger sorbent dosages, and for higher temperatures of heating. Almost the same amount of phosphate was released for both the 105°C and 160°C temperatures, with a sorbent dosage of 40g. This suggests that

105°C is the approximate threshold heating temperature that alters the crystal enough to cause significant "melting." Since the ammonium removal was lower at 105°C, compared with 160°C, but the "melting" was the same, it is recommended that the pellets should be heated to 160°C, in order to maximize ammonium removal.

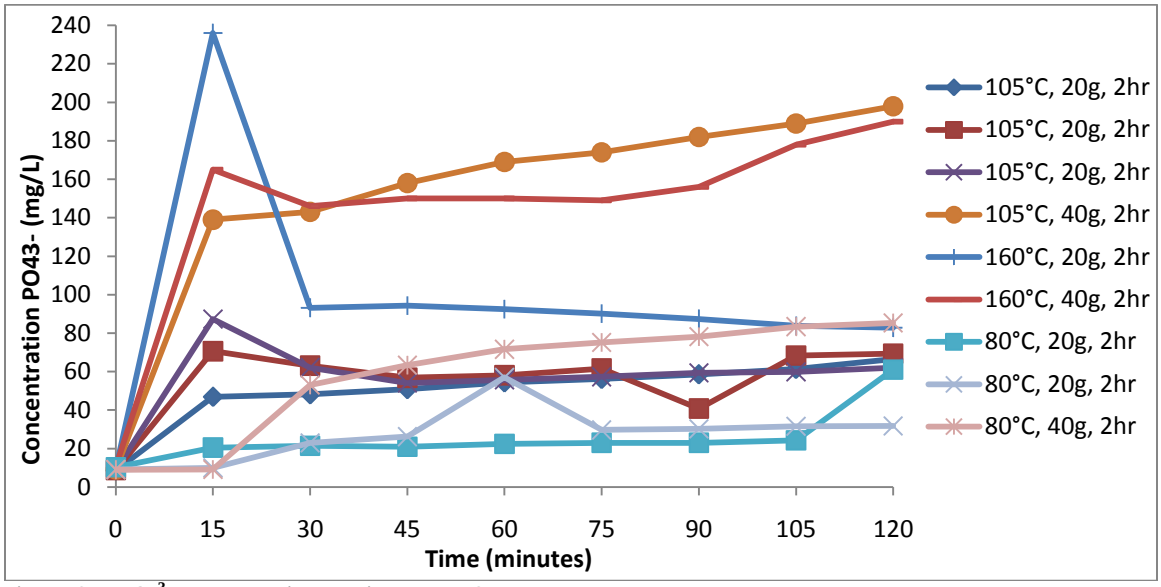

Figure 64 PO_4^{3-} concentration vs. time at pH 8.

5.6.1.3 Magnesium concentration versus time at constant pH 8

The magnesium concentration profile over time is shown for uptake experiments at constant pH 8 (Figure 65). The magnesium was released in large amounts only when heated at 160°C for both dosages. This seems to contradict the above argument regarding phosphate release. Perhaps the release of magnesium and phosphate is a function of heating temperature, sorbent quantity, as well as solubility conditions. This means that the reaction solutions are undersaturated with respect to phosphate and, thus, the largest sorbent quantity (80g/L) can supply enough through dissolution. On the other hand, magnesium may not be as undersaturated as phosphate is. Instead, the pellet became

soluble when heated to 160°C, regardless of sorbent quantity and may, in fact, cause supersaturation with respect to magnesium.

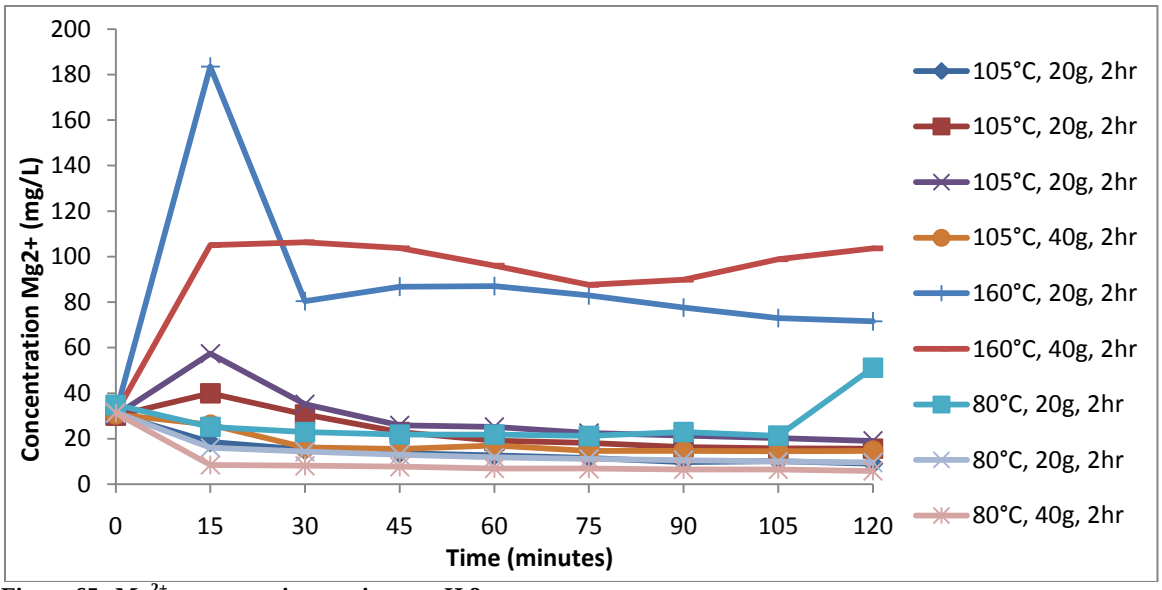

Figure 65 Mg^{2+} concentration vs. time at pH 8.

5.6.2 Uptake experiments at initial pH 8 with no control

An experiment was conducted to characterize the effectiveness of the uptake reaction when pH was initially set to 8, but not controlled thereafter. Results were compared to constant pH experiments.

5.6.2.1 Total ammonia concentration versus time at initial pH 8

The ammonium removal, when the pH was not controlled, was very poor (Figure 66). After the two hour reaction period, the solids were separated and the pH of the filtrate was increased to approximately pH 9-10. The ammonium removal achieved was the same as in the experiment at 160°C, with 80g/L of sorbent. This experiment shows that the pellets must be dissolving when the pH declines; leaving a source of magnesium and phosphate in solution that is subsequently removed when caustic is added to the filtrate.

In effect, controlling the pH may not be the best way to recycle struvite for ammonium removal. This contradicts Sugiyama et al. (2006) who found that ammonia removal increases when the pH is not controlled and allowed to decline from 8 to 6 over the duration of the reaction.

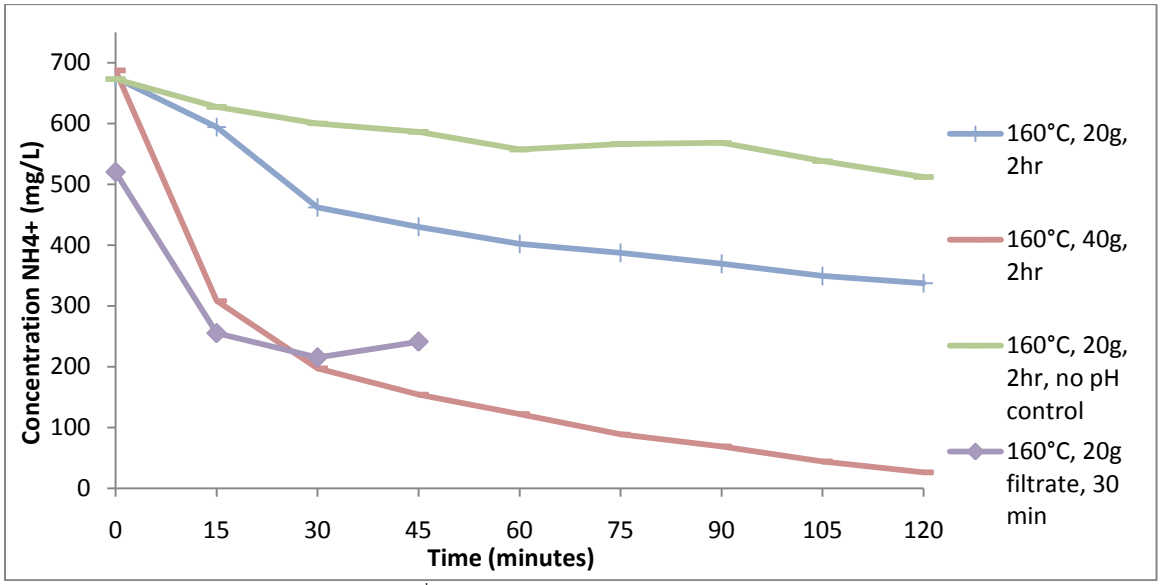

Figure 66 Effect of no pH control on NH_4^+ concentration.

5.6.2.2 Orthophosphate concentration versus time at initial pH 8

The pellets were confirmed to dissolve when the pH was not controlled (Figure 67). The two middle curves are data already shown in Figure 64 and are comparatively lower despite, being the previously largest phosphate release curves. Uncontrolled pH uptake reactions release large quantities of phosphate into solution because heated struvite is more soluble at more acidic pH. When the pH of the filtrate was increased, the phosphate immediately declined to approximately 20 mg/L, which is close to the initial value. This method is as effective at preventing phosphate from leaving the reactor as the experiments conducted at 80°C (Figure 64), with the added benefit of maximal ammonium removal.

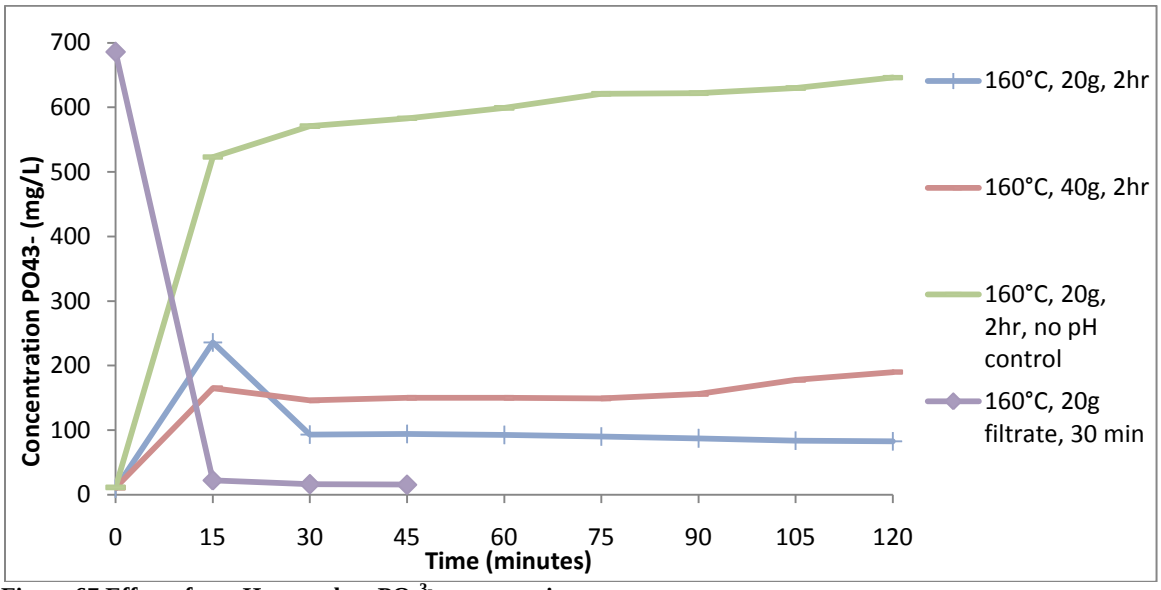

Figure 67 Effect of no pH control on PO_4^{3-} concentration.

5.6.2.3 Magnesium concentration versus time at initial pH 8

The uncontrolled pH also released substantially more magnesium compared to the controlled experiments (Figure 68). When the pH of the filtrate was raised, the magnesium immediately decreased down to 10 mg/L, which is close to the initial concentration.

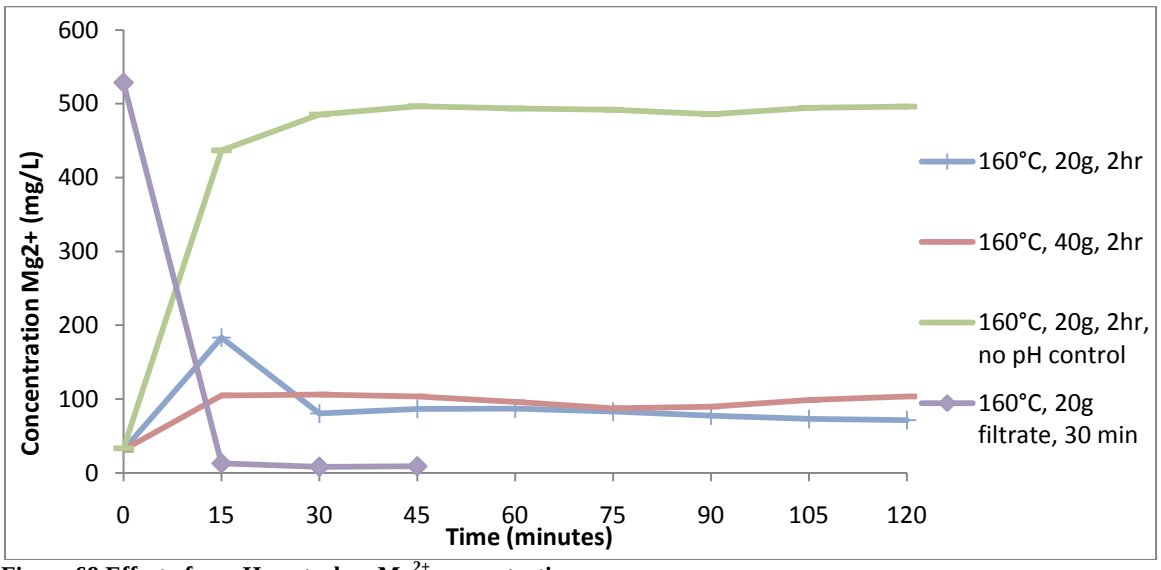

Figure 68 Effect of no pH control on Mg^{2+} concentration.

5.6.3 Uptake experiments at constant pH 9

Uptake experiments were conducted at a constant pH 9 and the three struvite components were sampled from solution every 15 minutes, over a reaction period of two hours. A comparison was made for different masses of sorbent added, and for different temperatures that the struvite was heated at.

5.6.3.1 Total ammonia concentration versus time at constant pH 9

The ammonia removal was greater for the larger sorbent additions (Figure 69). However, the ammonia removal was very poor compared to the corresponding experiments conducted at constant pH 8 (Figure 63). It appears as though increasing the pH reduces the viability of the ammonia recovery, using heated struvite.

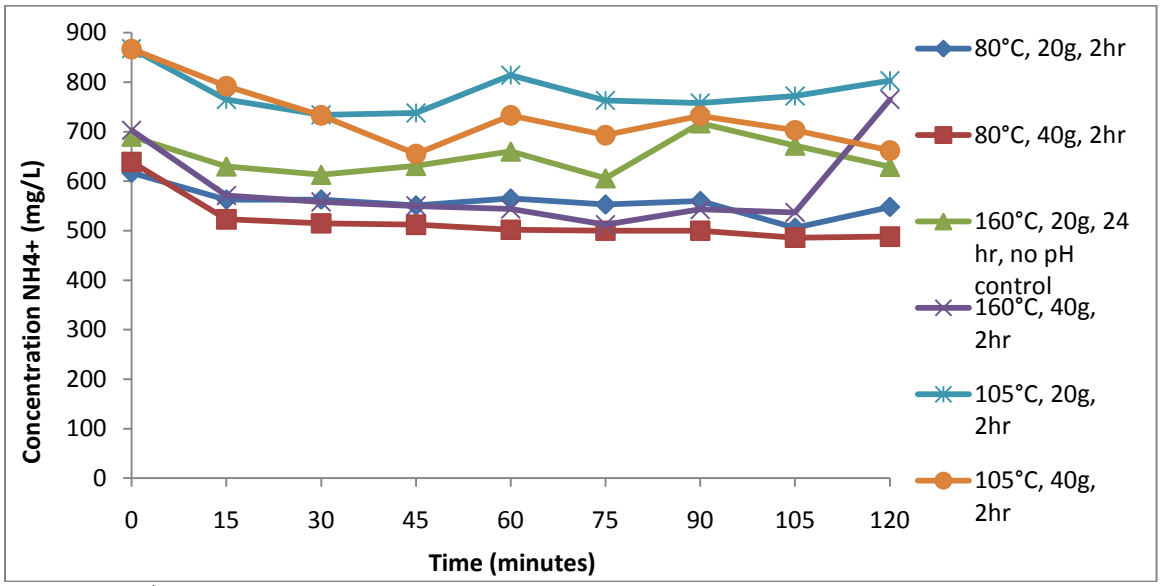

Figure 69 NH_4^+ concentration vs. time at pH 9.

5.6.3.2 Orthophosphate concentration versus time at constant pH 9

Orthophosphate concentrations versus time did not show a large change when the experiment was conducted at constant pH 9 (Figure 70). This is much different than at constant pH 8 (Figure 64), which showed that phosphate was released into solution in large quantities.

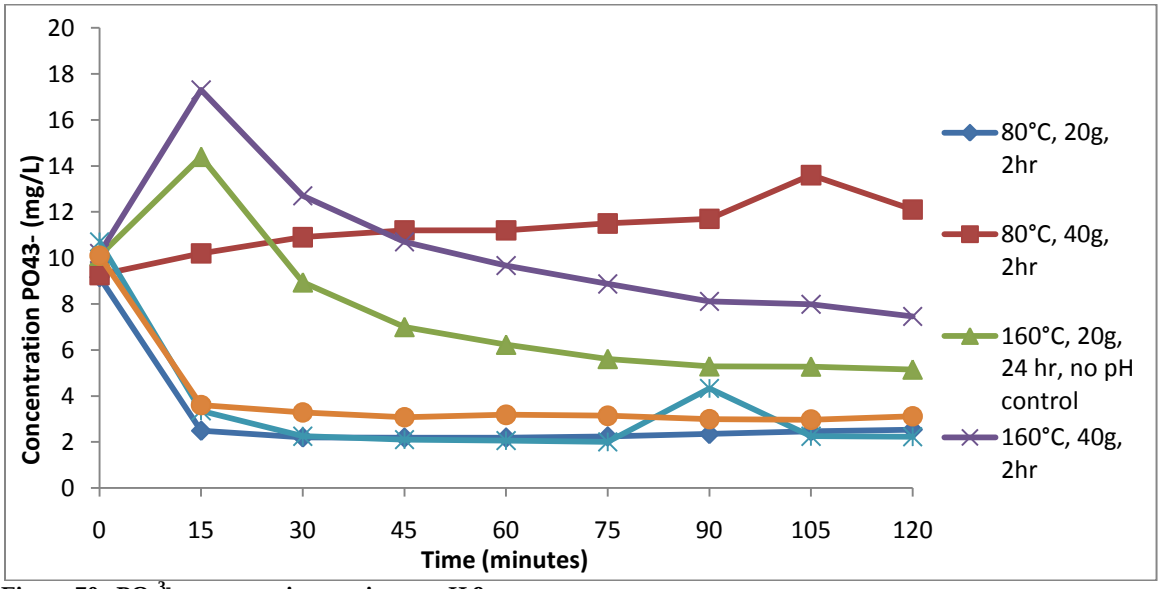

Figure 70 PO_4^{3-} concentration vs. time at pH 9.

5.6.3.3 Magnesium concentration versus time at constant pH 9

Magnesium concentrations increased for only the 160°C roasting temperatures, and decreased for all other experiments (Figure 71). This is similar to the result found at pH 8 (Figure 65). This means that at pH 9 the solutions may still be undersaturated with respect to magnesium, but not with respect to phosphate.

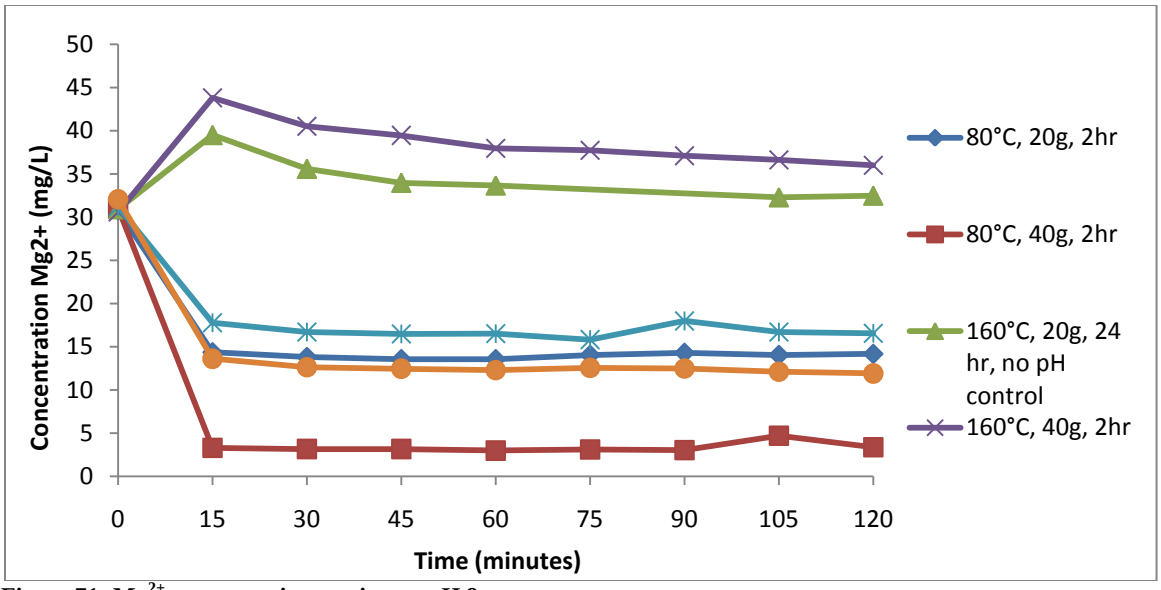

Figure 71 Mg^{2+} concentration vs. time at pH 9.

5.6.4 Molar ratios

Solid samples of roasted struvite, struvite after uptake, and fine struvite after uptake were dissolved with HCl and the concentrations of magnesium, ammonium, and phosphate were analyzed. Molar ratios were calculated for each experiment.

5.6.4.1 N:P ratios at pH 8

At pH 8, the N:P ratios for roasted struvite and struvite after uptake were in close agreement, except for one experiment (Figure 72). This suggests that ammonium does not become incorporated into the heated struvite crystal during the uptake reaction. The N:P ratio of uptake struvite in experiment nine was probably larger than the roasted struvite because the pH was not controlled in this experiment; this may have caused fine struvite to form and bond to the surface of the intact pellet. This is different than fines formed in solution, which are completely detached from the intact struvite pellets. Struvite fines that appear during the uptake reaction had an N:P ratio much closer to unity, suggesting that

struvite is the likely identity. The fines for the fifth experiment did not show the characteristic struvite N:P ratio. This is explainable because these pellets were only subjected to DI water in order to rehydrate the pellet and did not have access to external sources of ammonia. These fines may simply be fine fragments that broke away from the pellet during mixing, rather than newly formed fine struvite.

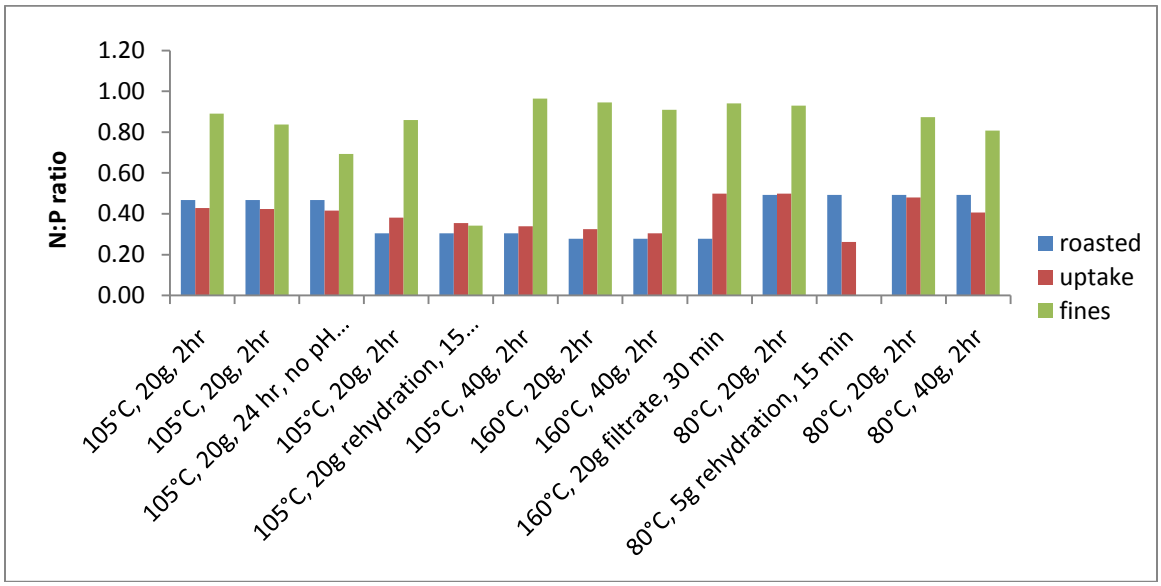

Figure 72 Solid product N:P ratios for uptake experiments at pH 8.

5.6.4.2 N:Mg ratios at pH 8

The N:Mg ratios at pH 8 followed nearly the same trends as the N:P ratios (Figure 73). These results suggest that classic struvite is not reformed in the intact pellets. Newly formed fines are probably closer in identity to pure struvite.

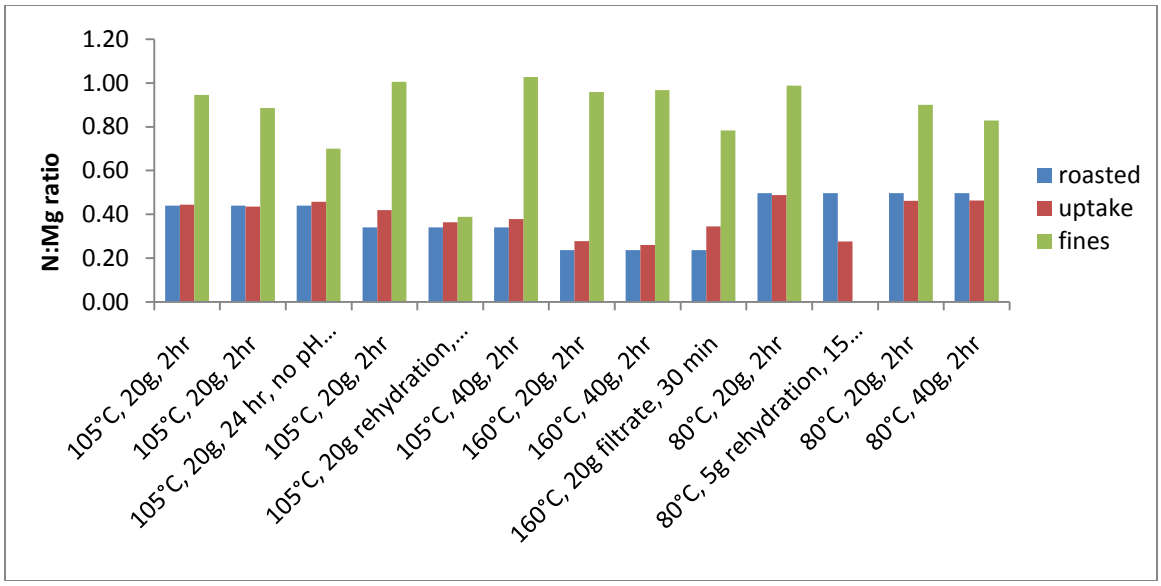

Figure 73 Solid product N:Mg ratios for uptake experiments at pH 8.

5.6.4.3 Mg:P ratios at pH 8

Theoretically, the Mg:P ratio should remain unchanged with a value of 1:1 for all three solid phases. This hypothesis was confirmed, because the Mg:P ratios for all twelve experiments are similar (within expected experimental errors) for the three solid phases (Figure 74).

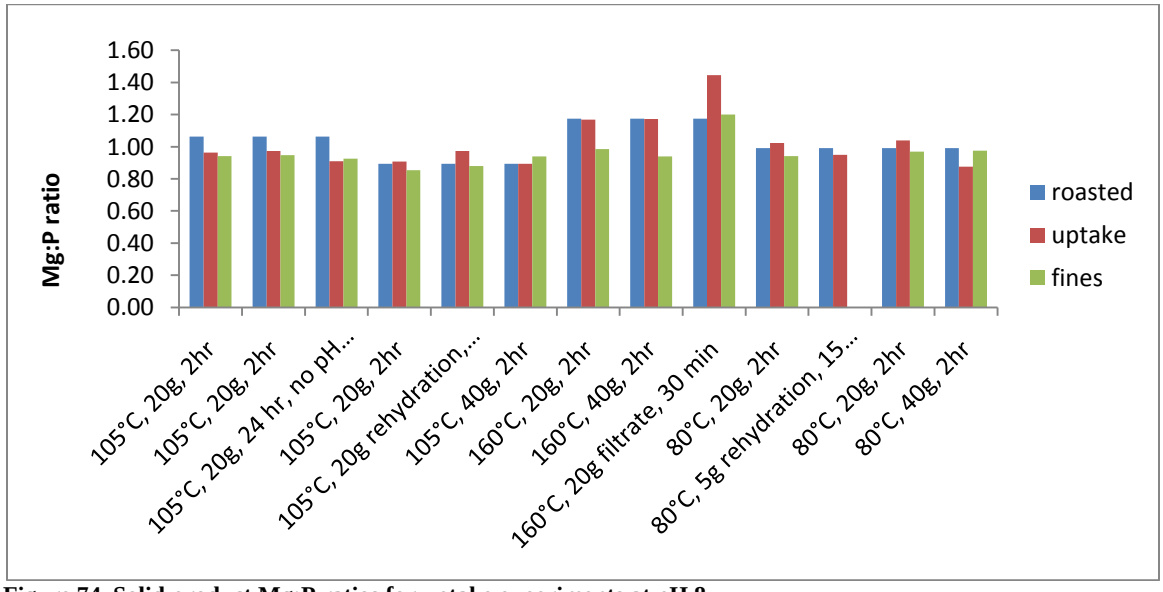

Figure 74 Solid product Mg:P ratios for uptake experiments at pH 8.

5.6.4.4 N:P ratios at pH 9

The N:P ratios were calculated for nine experiments done at constant pH 9 (Figure 75). The roasted and uptake samples generally had the same ratios, whereas the fines had a much higher ratio. These results agree with Stage one: 2009 results.

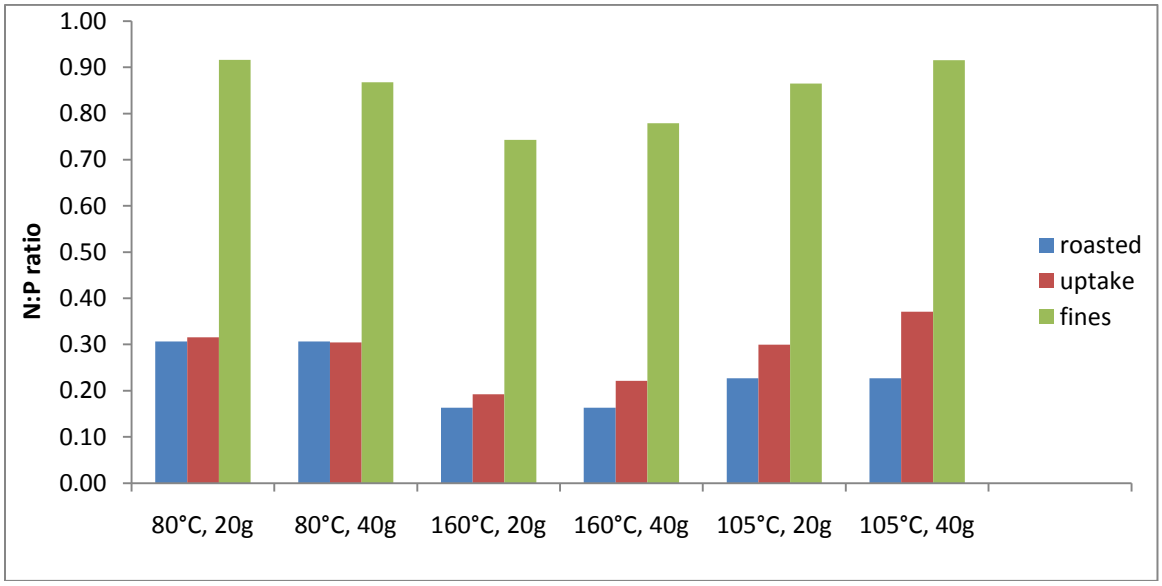

Figure 75 Solid product N:P ratios for uptake experiments at pH 9.

5.6.4.5 N:Mg ratios at pH 9

The N:Mg ratios at pH 9 followed nearly the same trends as the N:P ratios (Figure 76). In most instances, the roasted and uptake samples had very close to the same ratios. The fines usually had N:Mg ratios greater than 0.8, indicative of struvite formation, albeit impure.

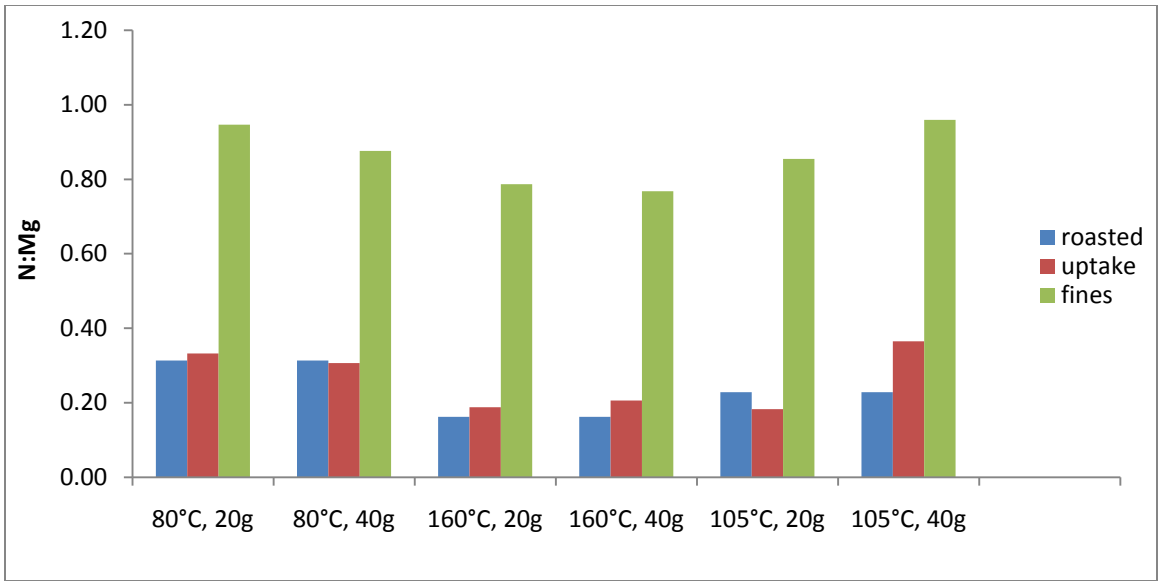

Figure 76 Solid product N:Mg ratios for uptake experiments at pH 9.

5.6.4.6 Mg:P ratios at pH 9

Mg:P ratios for the nine experiments conducted at pH 9 is shown in Figure 77. As expected, the characteristic struvite ratio was found for most samples. One samples has a large Mg:P ratio, likely as a result of an analysis error in magnesium or phosphate concentration.

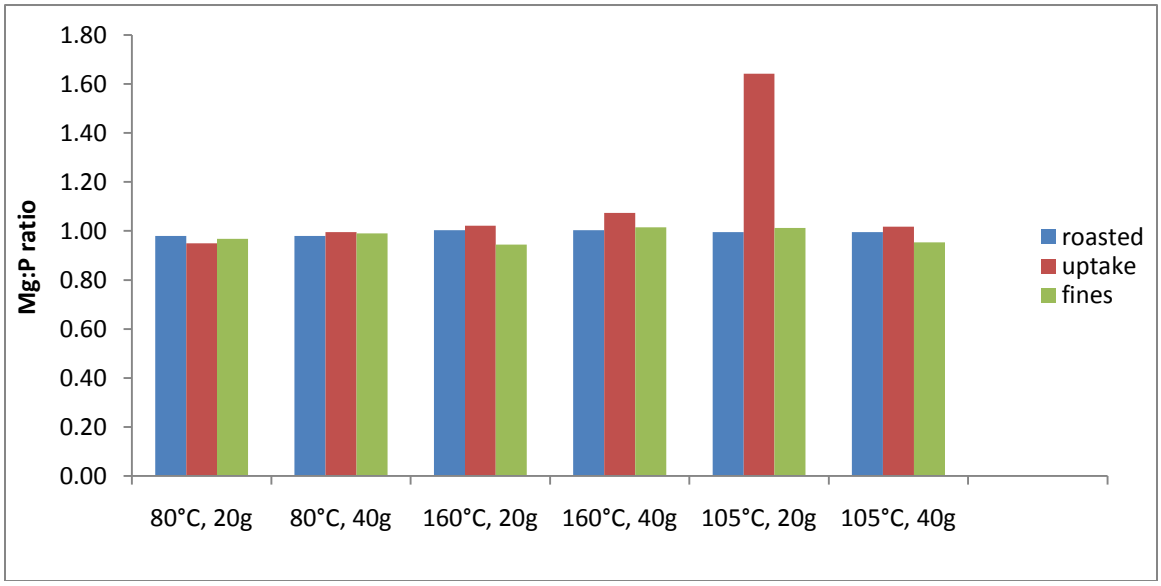

Figure 77 Solid product Mg:P ratios for uptake experiments at pH 9.

5.6.5 Full dissolution followed by reformation

In five experiments, the heated struvite was completely dissolved in acid to pH <2, containing 500 ml of feed solution. All residual ammonia in the pellets was released, as well as magnesium and phosphate. This solution was then increased up to pH 9-10 so that struvite could be crystallized again. These five experiments are hypothesized to follow the DR mechanism. The N:P ratio of the fines formed in these experiments was lower than expected (0.4-0.5) (Figure 78). The concentration of caustic used was quite high (6M) and likely increased the pH much past 9 in concentrated zones, in which other insoluble magnesium phosphates are formed, before struvite. It is also possible that during the quick increase of pH, the highly concentrated aqueous ammonia was able to escape into the atmosphere.

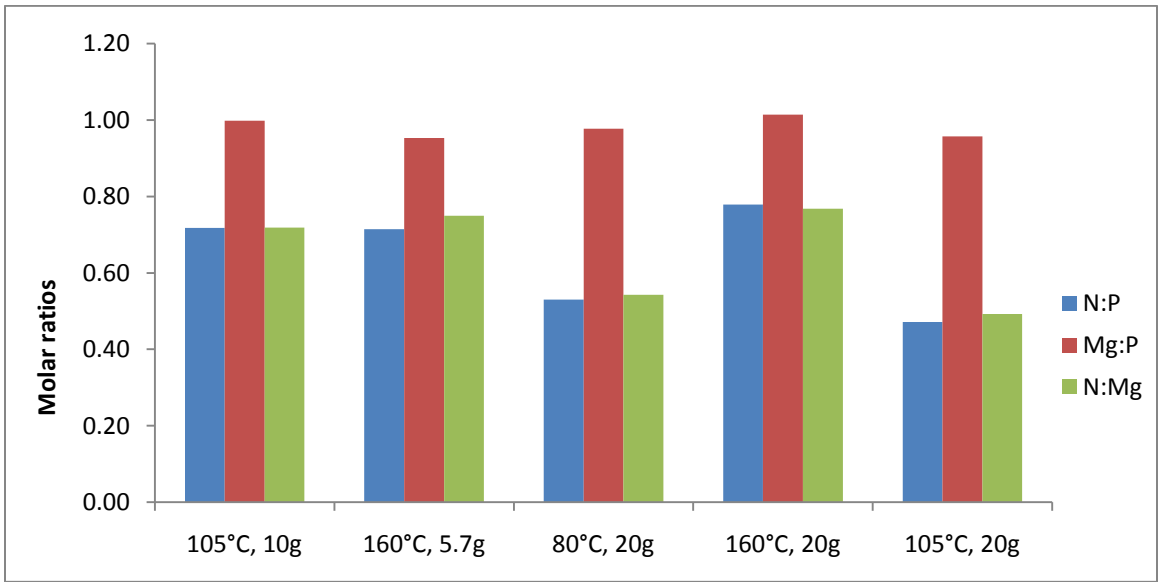

Figure 78 Effect of complete dissolution using acid prior to struvite crystallization for different heating temperatures and sample sizes.

Nitrogen mass balances were calculated for all samples and are shown in Figure 79-83. Since no pellets were formed, the ammonia in the feed was incorporated into newly

formed fine struvite. The nitrogen mass remained slightly imbalanced for all experiments (87-127%), despite the lack of pellets which are known to adsorb water. Four of the five experiments had a reduction in mass, as expected, due to ammonia evaporation. One of the five experiments had a gain in mass, which may have occurred if the fines were not completely dry.

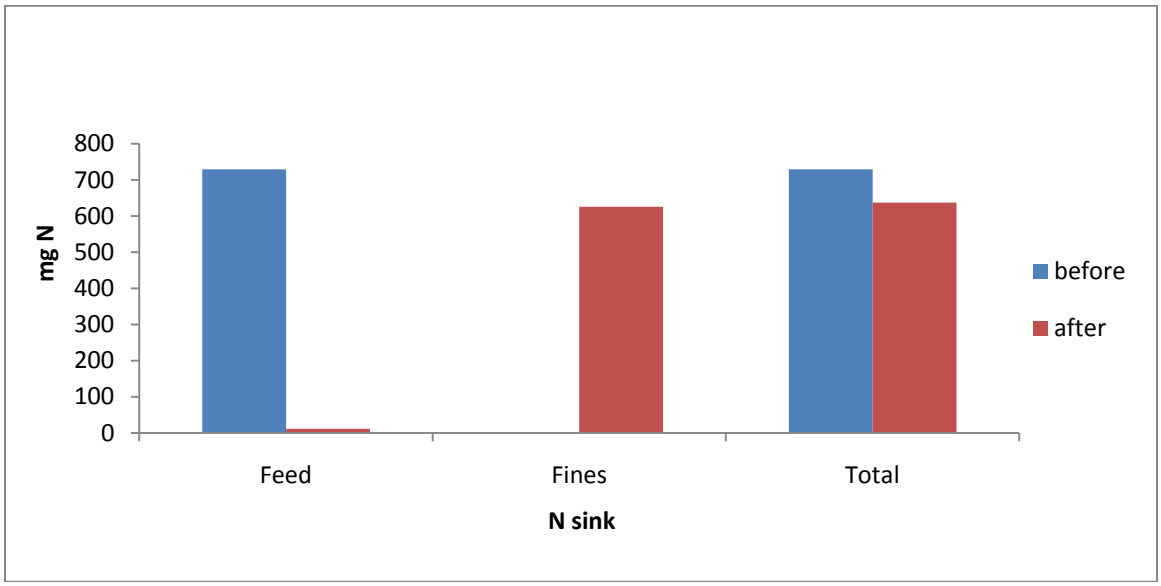

Figure 79 Nitrogen balance for 10g complete dissolution and reformation for a heating temperature of 105°C.

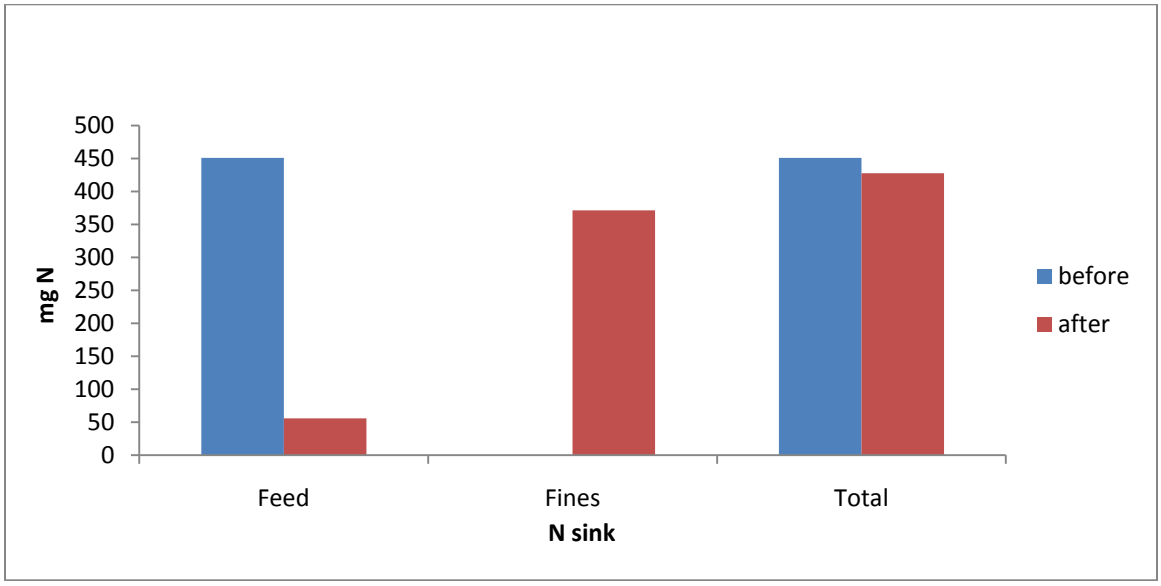

Figure 80 Nitrogen balance for 5.7g complete dissolution and reformation for a heating temperature of 160°C.

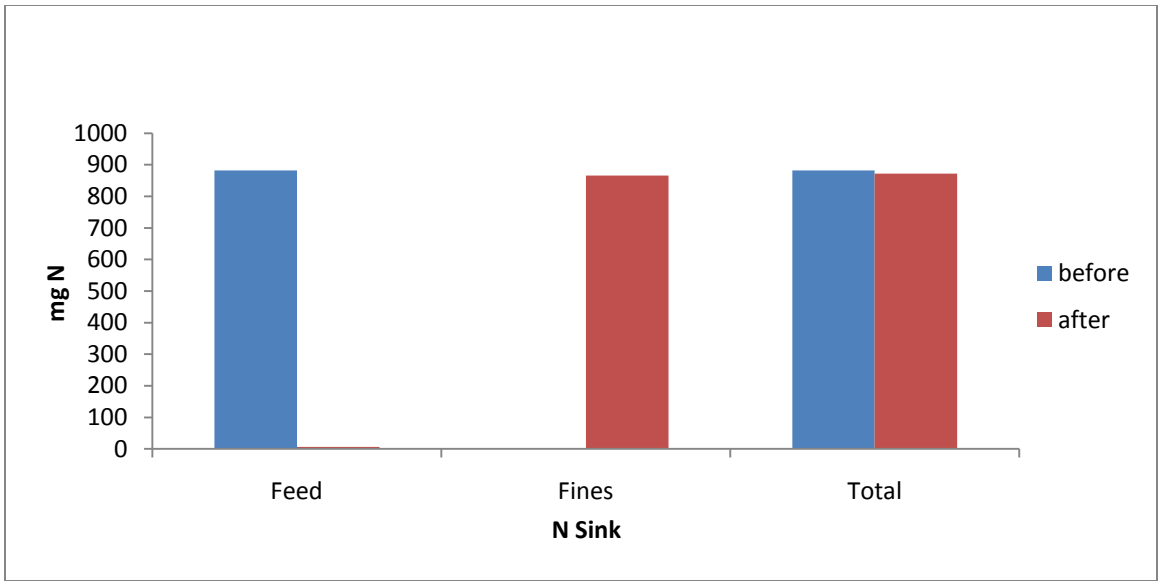

Figure 81 Nitrogen balance for 20g complete dissolution and reformation for a heating temperature of 80°C.

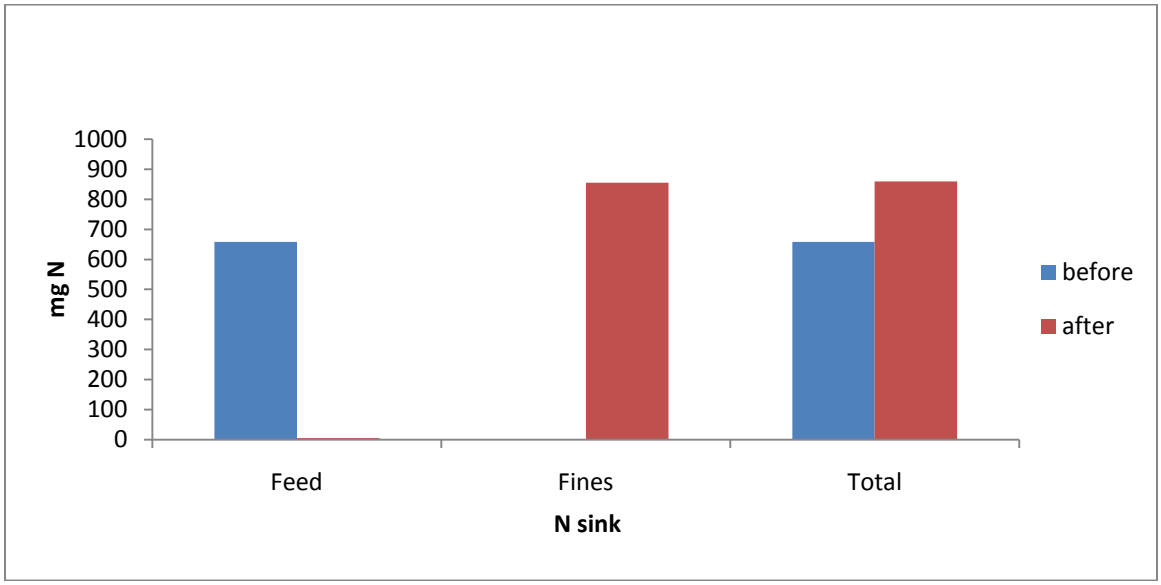

Figure 82 Nitrogen balance for 20g complete dissolution and reformation for a heating temperature of 160°C.

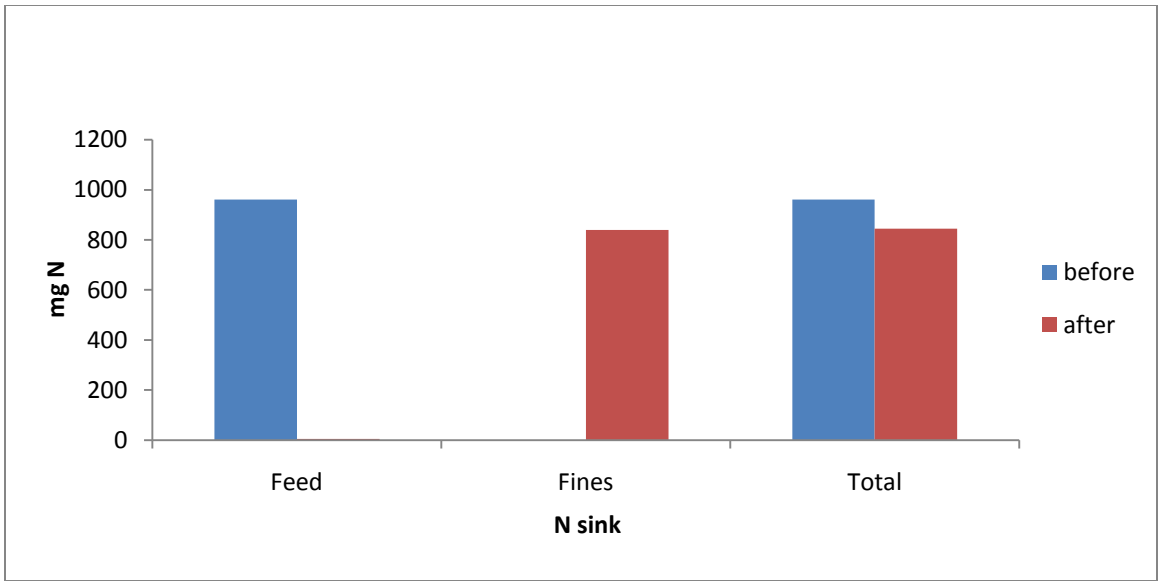

Figure 83 Nitrogen balance for 20g complete dissolution and reformation for a heating temperature of 105°C.

5.7 Mass balance

The mass balances for nitrogen, phosphorus, and magnesium for 2009 experiments, ranged from 75-122%, 63-202%, and 67-191%, respectively as shown in the source and sink budgets in Appendix D. There is no clear trend showing the flow of the different components between sources and sinks, despite the evidence based on molar ratios in favour of a DR mechanism.

5.8 Specific uptake

The specific uptake was calculated for each experimental condition and shown in Figure 84-86. There are no clear trends. It looks as though the specific uptake decreases as the temperature of heating increases, although this result needs to be replicated in order to be valid. It also appears that pH 9 may have a higher specific uptake compared to pH 8 (which dissolves struvite too much) and pH 10 (which does not dissolve struvite to provide enough source ions). Stefanowicz et al. (1992) achieved a much higher specific ammonia removal rate at approximately 71.4 mg N/ g roast product.

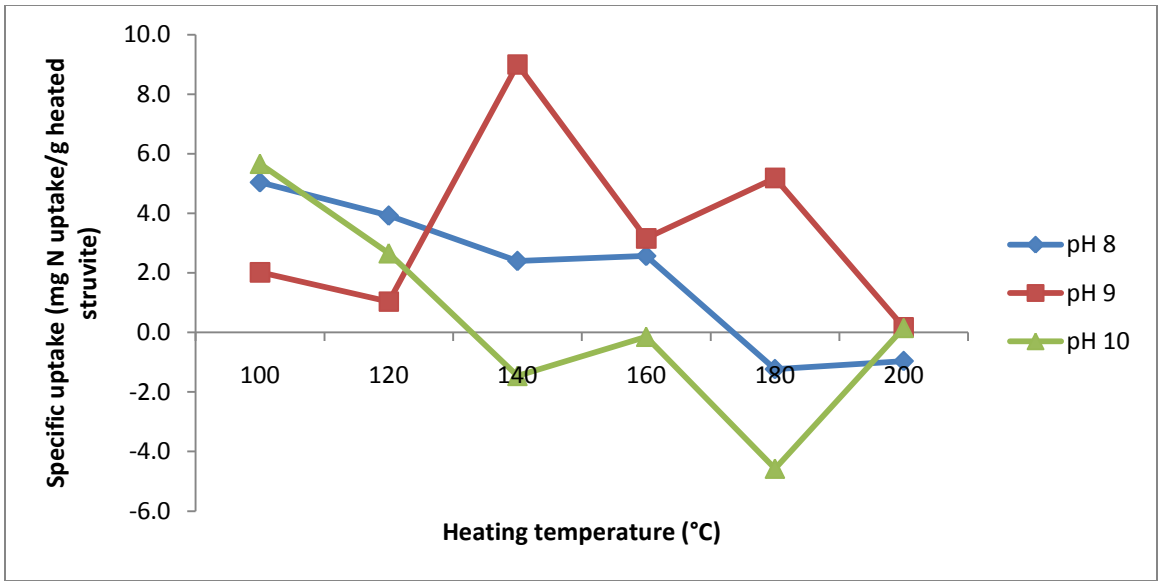

Figure 84 2009 specific uptake versus heating temperature for three pH values.

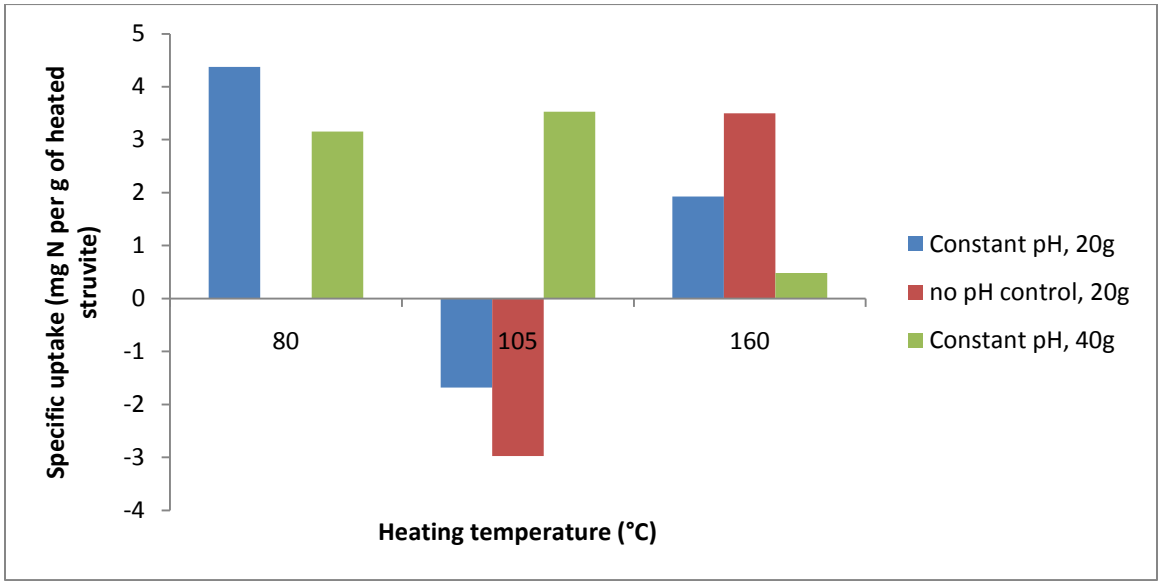

Figure 85 2010 specific uptake versus heating temperature at pH 8.

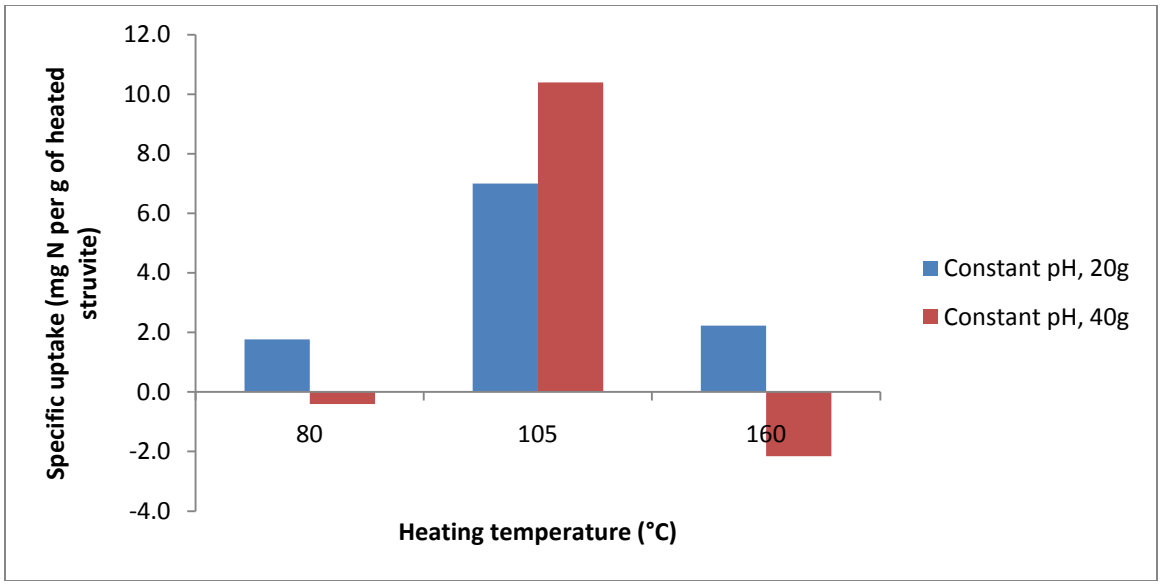

Figure 86 2010 specific uptake versus heating temperature at pH 9.

5.9 SEM results

The inside of a raw Gold Bar struvite pellet is shown in Figure 87 and Figure 89. A distinct "onion" layering is observed, due to the nature of formation of crystal aggregation in the fluidized bed reactor. Heating the pellet causes cracks along the surface of the layers as the bulk structure weakens, releasing water and ammonia (Figure 88). At 500 times magnification, the raw struvite is seen to have a generally smooth surface (Figure 90), whereas the roasted struvite has a much rougher "needle-like" surface due to the extensive fracturing (Figure 91). For an uptake pH of both 8.5 and 10.5, the pellet morphology is observed to have a "dulling" characteristic (Figure 92-95). The cracked structures still exist, but the needle-like crystals are replaced by a more rounded globular formation. This may be the result of dissolution of the needle-like magnesium hydrogen phosphate crystals with subsequent struvite reformation to fill in the crevices.

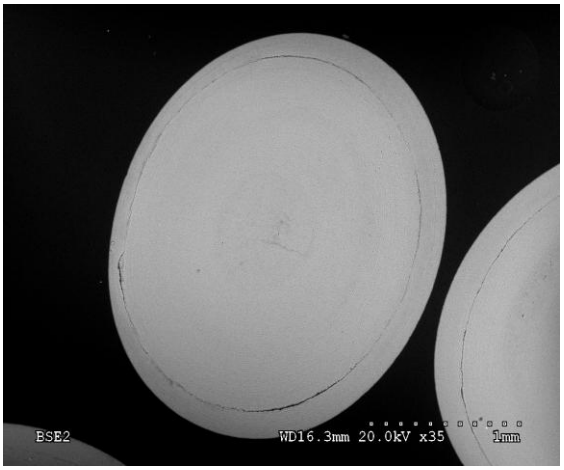

Figure 87 Raw Gold Bar struvite interior 35x.

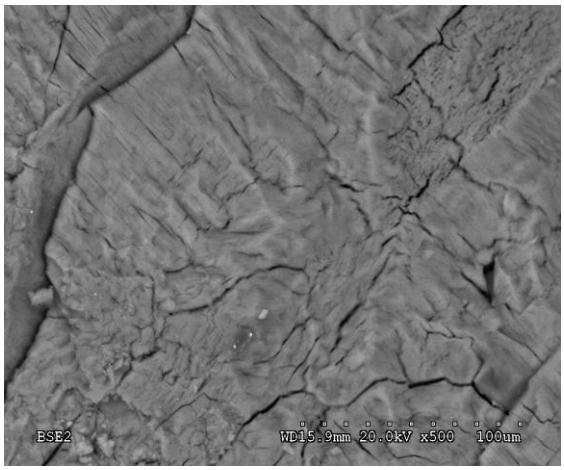

Figure 90 Raw Gold Bar Struvite cut 500x interior.

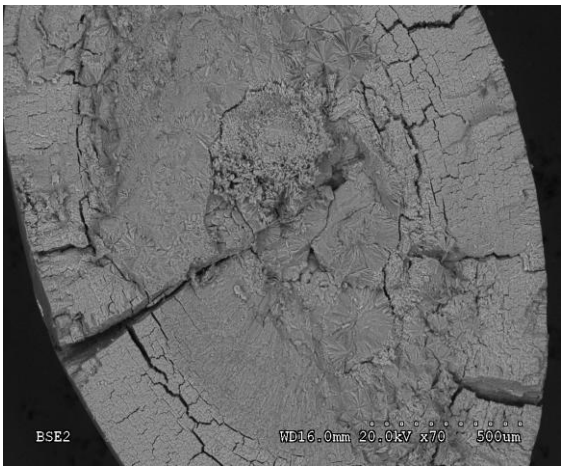

Figure 88 Heated Gold Bar struvite interior 70x.

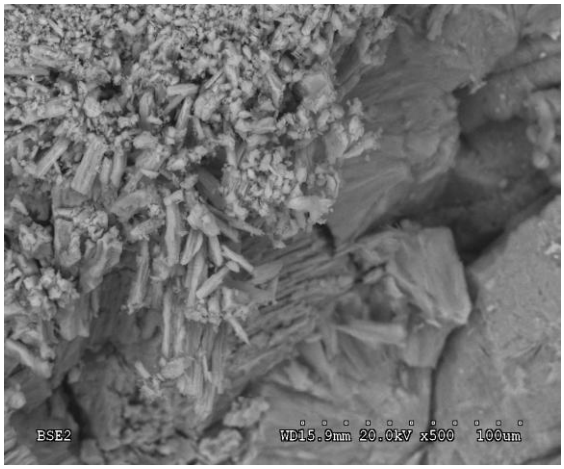

Figure 91 Heated Gold Bar struvite 500x interior.

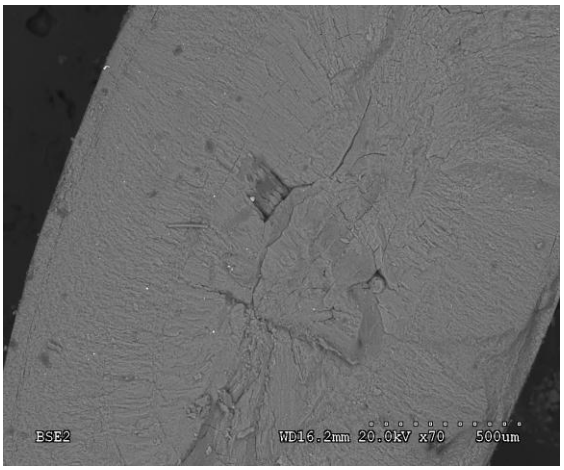

Figure 89 Raw Gold Bar struvite interior 70x.

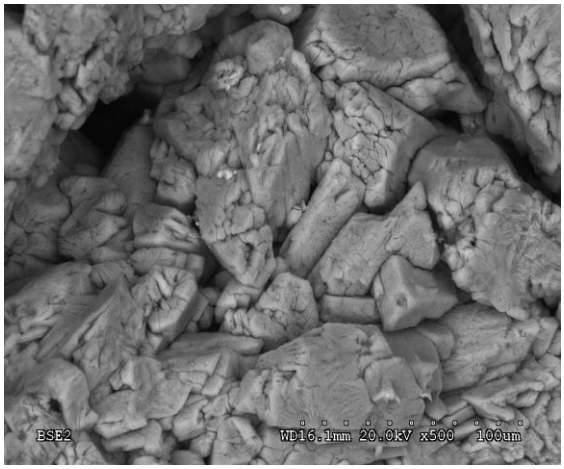

Figure 92 Uptake pH 8.5 cut 500x interior.

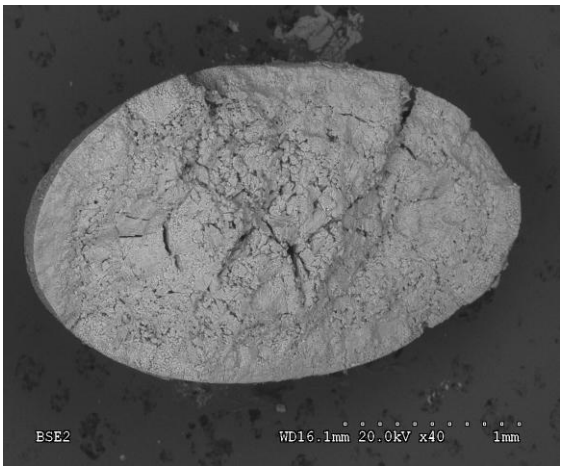

Figure 93 Uptake pH 8.5 cut 40x.

Figure 94 Uptake pH 10.5 cut 40x.

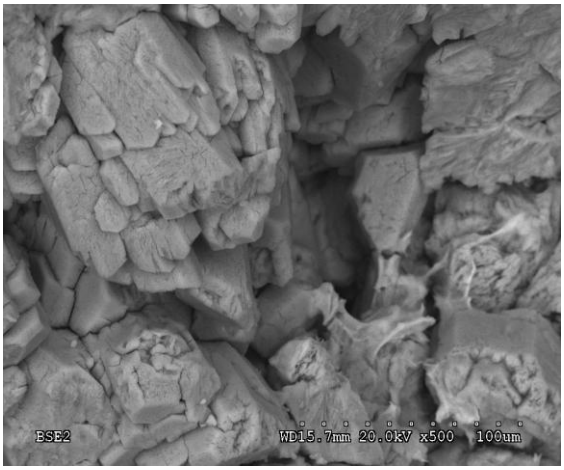

Figure 95 Uptake pH 10.5 cut 500x interior.

5.10 Preliminary economic analysis

A preliminary economic analysis was conducted to determine the possible costs involved with this ammonia recovery approach. The four major costs involved are for purchasing raw struvite, caustic, electricity, and labour. It is assumed that the cost of purchasing raw struvite is $3000/tonne. Also, to determine the amount of centrate produced per year, the average 2009 flow and BOD removals at Lulu Island WWTP were retrieved and used from Metro Vancouver, with values of 76.2 MLD and 550lb/ML, respectively. Other assumptions include the sludge specific gravity equal to 1.02 (Viessman & Hammer,

2004), BOD utilization rate of 0.05 lb cells/lb BOD utilized (Viessman & Hammer, 2004), 0.5% of influent flow becoming sludge flow (Constantine, 2006), and 75% of sludge flow becoming centrate flow (Viessman & Hammer, 2004). The caustic price is assumed to be $500/tonne. The electricity price is assumed to be $0.02817/kwh as per BC Hydro's business rates. The mixer is assumed to have an efficiency of 90%. Labour costs are assumed to be $120/day (Britton et al., 2005).

The cost summary to treat this volume of wastewater (with Lulu Island WWTP characteristics) is shown in Table 10. The largest cost is for purchasing the raw struvite because it is a very valuable commodity. However, if prices fluctuate and moved downward, this cost might be reduced. The detailed spreadsheet calculations are shown in Appendix E.

Table 10 Economic analysis.

Price component	Cost per day ($/day)
Struvite	8670
Caustic	805
Electricity	217
Labour	120
Total	9812

For a valid economic analysis, this technique must be compared to an alternative, such as side stream biological nitrification. Right now in Metro Vancouver, ammonia discharge concentrations are not enforced because it is deemed that ammonia toxicity is not a high priority issue. However, facilities such as the Hyperion Waste Water Treatment Plant in Los Angeles, California, nitrify the digester supernatant and centrate in order to prevent ammonia toxicity in Santa Monica Bay. Therefore, an approach assuming Lulu Island WWTP will also one day side stream nitrify the digester centrate has been selected. To reduce the ammonia from 700mg/L to the EPA guideline of 5mg/L with the Lulu Island WWTP flows it would require about 1620 kg/day of oxygen. At a cost of $0.2/kg O_2, the

daily oxygen cost would be about $320. Assuming the wastewater contains 100mg/L alkalinity as $CaCO_3$, the amount which must be replaced, is approximately 1113 kg/day of $CaCO_3$. This cost would sum to $334 per day, assuming a price of $0.3/kg $CaCO_3$. Thus, the total daily cost to nitrify the centrate to non toxic concentrations, would be about $650. Therefore, the preliminary economic analysis has found that conventional side stream nitrification of anaerobic centrate is about 15 times cheaper per day. This analysis depends on the assumption that ammonia toxicity is an issue to be addressed. Of course if ammonia toxicity is not a problem, then both of these processes should not be implemented, solely based on cost.

6 Conclusions

The results of the preliminary bench-scale research on ammonia removal and recovery, using heated struvite as an adsorbent, yielded the following conclusions:

- The 24-hour isothermal decomposition temperature of struvite at atmospheric pressure and moisture conditions was between 60-80°C.
- Struvite is not completely decomposed to amorphous newberyite because the N:P ratios remain at 0.2-0.3. The product is likely a mixture of magnesium phosphates.
- Higher heating temperature caused both the amount of ammonia and water released to be increased.
- Only 0.5-1 hour was necessary at 100-200°C to decompose struvite and remove about 70% of nitrogen.
- Sample surface area or sample location source did not seem to have an effect on the heating of a bulk struvite sample.
- The environment and duration have a large effect on the amount of water re-adsorbed onto the crystal after heating. Vacuum desiccation at 17in Hg was not sufficient to prevent this effect.
- Higher heating temperatures had proportionally higher water adsorption rates, on decomposed pellets.
- A trade off exists; ammonia removal can be achieved, up to 99%, using heated struvite as an adsorbent, which must first dissolve, ruining the marketable pellet form.

- Phosphate and magnesium are released from the pellet form into solution, due to the high solubility of heated struvite.
- The molar ratios data revealed that only newly-formed fines were struvite whereas the pellet struvite was a mixture of different magnesium phosphates.
- Newly formed fines possess molar ratios characteristic of pure struvite.
- Pellets did not possess molar ratios characteristic of pure struvite after the uptake reaction. The molar ratios resembled heated struvite pellets.
- Pellets showed a small fractional increase in nitrogen content, due to surface adsorption by fines.
- If a different technology could make use of struvite as an adsorbent of ammonia nitrogen, without any material losses, then this technology might be more cost effective at full scale compared to conventional side stream nitrification.

7 Recommendations

Based on the results of the bench scale experiments on ammonia removal and recovery using struvite as an adsorbent, the following recommendations are proposed:

- XRD analyses should be conducted in order to construct phase diagrams after heating struvite.
- Real-time TGA-MS or TGA-IR analyses run to precisely determine if water and ammonia are evolved at the same temperature and time.
- Use a better vacuum desiccation system to control atmospheric moisture from adsorbing or absorbing onto struvite pellets
- Determine if struvite can be decomposed into newberyite at high vacuum, at room temperature.
- Do more elemental analyses between 60-80°C, to probe closer to the true decomposition temperature.
- An elemental analysis should be run on a sample that is rehydrated for longer than 5 minutes, after heating, to allow for a longer time for water to access the whole pellet and potentially regain hexahydration.
- Determine the identity of the product after heating at 160°C and above, to determine the source of the Mg:P ratio between 1.2-1.5.
- The viability of collecting the evolved ammonia, using a resin or boric acid or by a common fertilizer method, should be investigated.

- The effects of scaling up to pilot scale should be determined to check what happens to attrition rates, ammonium removals, and phosphate and magnesium release into solution.
- More rigorous and controlled experimental conditions must be maintained from heating through to uptake, in order to properly mass balance the three components that make up struvite.
- Determine the economic viability of completely acid dissolving heated struvite as a source of magnesium and phosphate, for subsequent removal of excess ammonia.

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Appendix A: Instrument operational parameters

Table A. 1 Magnesium AA operating parameters

Species Analyzed	Magnesium-Mg^{2+}
Concentration Units	mg/L
Instrument mode	Absorbance
Sampling mode	Autonormal
Calibration mode	Concentration
Measurement mode	Integrate
Replicates standard	3
Replicates sample	3
Wavelength	202.6 nm
Range	0-100 mg/L
Flame type	N_2O/C_2H_2
Calibration algorithm	New rational
Lamp current	4.0 mA

Table A. 2 Lachat parameters for ammonia and phosphate

Species Analyzed	PO_4-P	NH_3-N
Concentration Units	mg/L	mg/L
Range	0-100 mg/L	0-100 mg/L
Temperature	63°C	63°C
Method	Ammonia Molybdate	Phenate
Reference	1	2

1: LaChat Instruments Methods Manual for the QuikChem Automated Ion Analyzer (1990). QuikChem method number 10-115-01-1Z

2: APHA, AWWA, WPCF (1995). Method 4500-NH3-F. Phenate Method

Appendix B: Mass balance data

Table B. 1 2009 nitrogen balance 100°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc N as NH3	mg/L	112	102	105
	Vol. sample	L	0.05	0.05	0.05
	Wt sample for digesting	mg	200	200	200
	Wt struvite for uptake	mg	50000	50040	49990
	Amount of N in roasted struvite	mg	1400.00	1276.02	1312.24
	Amount of N in roasted struvite	g	1.40	1.28	1.31
	Feed				
	Conc N as NH3	mg/L	295	300	321
	Vol. sample	L	0.75	0.75	0.75
	Amount of N in feed	mg	221.25	225	241
	Amount of N in feed	g	0.22125	0.225	0.24
	Total N to start	**g**	**1.62**	**1.50**	**1.55**
	Proportion of Mass N in feed		0.1364688	0.149898069	0.155023785
	Proportion of N in calcinated pellets		0.8635312	0.850101931	0.844976215
	END				
	Uptake: struvite				
	Conc N as NH3	mg/L	89.4	72.3	87.8
	Vol. sample	L	0.05	0.05	0.05
	Wt sample for digesting	mg	200	200	200
	Wt struvite after uptake	mg	73910	76180	72690
	Amount of N in struvite after uptake	mg	1651.89	1376.95	1595.55
	Amount of N in struvite after uptake	g	1.65	1.38	1.60
	Fines				
	Conc N as NH3	mg/L	211	196	216
	Vol. sample	L	0.05	0.05	0.05
	Wt sample for digesting	mg	200	200	200
	Wt fines	mg	2610	1490	1540
	Amount of N in fines	mg	137.68	73.01	83.16
	Amount of N in fines	g	0.14	0.07	0.08
	Filter Paper				
	Conc N as NH3	mg/L	67.6	39.1	94.3
	Vol. sample	L	0.05	0.05	0.05
	Amount of N on filter paper	mg	3.38	1.96	4.72
	Amount of N in filter paper	g	0.00	0.00	0.00
	Feed				
0 mins	Conc N as NH3	mg/L	324.2	219	281
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.001621	0.001095	0.001405
15 mins	Conc N as NH3	mg/L	187	188	229

	Sample	Unit	pH 8	pH 9	pH 10
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000935	0.00094	0.001145
30 mins	Conc N as NH3	mg/L	133	167	218
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000665	0.000835	0.00109
45 mins	Conc N as NH3	mg/L	107	158	207
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000535	0.00079	0.001035
60 mins	Conc N as NH3	mg/L	84.5	162	196
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0004225	0.00081	0.00098
75 mins	Conc N as NH3	mg/L	63.8	158	206
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000319	0.00079	0.00103
90 mins	Conc N as NH3	mg/L	45.2	155	202
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000226	0.000775	0.00101
105 mins	Conc N as NH3	mg/L	36.6	153	213
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000183	0.000765	0.001065
120 mins	Conc N as NH3	mg/L	25.2	156	206
	Vol. sample	L	0.71	0.71	0.71
	Ammount of N in feed	g	0.017892	0.11076	0.14626
	TOTAL N AT END	**g**	**1.82**	**1.57**	**1.84**
	Mass N remain in soln (g)		**0.02**	**0.11**	**0.15**
	Mass in fines + filter (g)		**0.14**	**0.07**	**0.09**
	Mass N in uptake pellets (g)		**1.65**	**1.38**	**1.60**
	Mass N lost during sampling (g)		**0.00**	**0.01**	**0.01**
	DIFFERENCE	**g**	**-0.19**	**-0.07**	**-0.29**
	Reduction of mass in solution		0.20	0.11	0.09
	RECOVERY (%)		**112**	**105**	**118**

Table B. 2 2009 nitrogen balance 120°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc N as NH3	**mg/L**	105	90.1	105
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50030	49990
	Amount of N in roasted struvite	**mg**	1312.50	1126.93	1312.24
	Amount of N in roasted struvite	**g**	1.31	1.13	1.31
	Feed				
	Conc N as NH3	**mg/L**	290	314	327
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of N in feed	**mg**	217.5	235.5	245
	Amount of N in feed	**g**	0.2175	0.2355	0.25
	Total N to start	**g**	**1.53**	**1.36**	**1.56**
	Proportion of Mass N in feed		0.1421569	0.172853456	0.157468148
	Proportion of N in calcinated pellets		0.8578431	0.827146544	0.842534852
	END				
	Uptake: struvite				
	Conc N as NH3	**mg/L**	84.9	61.5	73.4
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	71070	76670	78760
	Amount of N in struvite after uptake	**mg**	1508.46	1178.80	1445.25
	Amount of N in struvite after uptake	**g**	1.51	1.18	1.45
	Fines				
	Conc N as NH3	**mg/L**	217	201	222
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	3670	2010	1850
	Amount of N in fines	**mg**	199.10	101.00	102.68
	Amount of N in fines	**g**	0.20	0.10	0.10
	Filter Paper				
	Conc N as NH3	**mg/L**	77.8	50	139
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of N on filter paper	**mg**	3.89	2.50	6.95
	Amount of N in filter paper	**g**	0.00	0.00	0.01
	Feed				
0 mins	Conc N as NH3	**mg/L**	319	168	230
	Vol. sample	**L**	0.005	0.005	0.005

	Sample	Unit	pH 8	pH 9	pH 10
	Ammount of N in feed	g	0.001595	0.00084	0.00115
15 mins	Conc N as NH3	mg/L	170	138	185
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00085	0.00069	0.000925
30 mins	Conc N as NH3	mg/L	115	133	166
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000575	0.000665	0.00083
45 mins	Conc N as NH3	mg/L	89.5	124	165
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0004475	0.00062	0.000825
60 mins	Conc N as NH3	mg/L	71.8	116	161
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000359	0.00058	0.000805
75 mins	Conc N as NH3	mg/L	52.4	117	167
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000262	0.000585	0.000835
90 mins	Conc N as NH3	mg/L	36.3	112	160
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0001815	0.00056	0.0008
105 mins	Conc N as NH3	mg/L	25.4	108	159
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000127	0.00054	0.000795
120 mins	Conc N as NH3	mg/L	17.4	102	153
	Vol. sample	L	0.71	0.71	0.71
	Ammount of N in feed	g	0.012354	0.07242	0.10863
	TOTAL N AT END	**g**	**1.73**	**1.36**	**1.67**
	Mass N remain in soln (g)		**0.01**	**0.07**	**0.11**
	Mass in fines + filter (g)		**0.20**	**0.10**	**0.11**
	Mass N in uptake pellets (g)		**1.51**	**1.18**	**1.45**
	Mass N lost during sampling (g)		**0.00**	**0.01**	**0.01**
	DIFFERENCE	**g**	**-0.20**	**0.00**	**-0.11**
	Reduction of mass in solution		0.20	0.16	0.13
	RECOVERY (%)		**113**	**100**	**107**

Table B. 3 2009 nitrogen balance 140°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc N as NH3	**mg/L**	89.9	59.6	86.1
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50000	50010
	Amount of N in roasted struvite	**mg**	1123.75	745.00	1076.47
	Amount of N in roasted struvite	**g**	1.12	0.75	1.08
	Feed				
	Conc N as NH3	**mg/L**	300	286	316
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of N in feed	**mg**	225	214.5	237
	Amount of N in feed	**g**	0.225	0.2145	0.24
	Total N to start	**g**	**1.35**	**0.96**	**1.31**
	Proportion of Mass N in feed		0.1668211	0.223553934	0.180438729
	Proportion of N in calcinated pellets		0.8331789	0.776446066	0.819561271
	END				
	Uptake: struvite				
	Conc N as NH3	**mg/L**	74.3	67.3	51.3
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	66950	71010	78250
	Amount of N in struvite after uptake	**mg**	1243.60	1194.74	1003.56
	Amount of N in struvite after uptake	**g**	1.24	1.19	1.00
	Fines				
	Conc N as NH3	**mg/L**	208	145	248
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	6170	4140	4380
	Amount of N in fines	**mg**	320.84	150.08	271.56
	Amount of N in fines	**g**	0.32	0.15	0.27
	Filter Paper				
	Conc N as NH3	**mg/L**	110	81.5	196
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of N on filter paper	**mg**	5.50	4.08	9.80
	Amount of N in filter paper	**g**	0.01	0.00	0.01
	Feed				
0 mins	Conc N as NH3	**mg/L**	329	193	218
	Vol. sample	**L**	0.005	0.005	0.005

	Sample	Unit	pH 8	pH 9	pH 10
	Ammount of N in feed	g	0.001645	0.000965	0.00109
15 mins	Conc N as NH3	mg/L	164	103	130
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00082	0.000515	0.00065
30 mins	Conc N as NH3	mg/L	97.9	79.3	115
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0004895	0.0003965	0.000575
45 mins	Conc N as NH3	mg/L	54.8	61.3	104
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000274	0.0003065	0.00052
60 mins	Conc N as NH3	mg/L	35	47.2	100
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000175	0.000236	0.0005
75 mins	Conc N as NH3	mg/L	26	28.9	98
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00013	0.0001445	0.00049
90 mins	Conc N as NH3	mg/L	13.8	15.6	91
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000069	0.000078	0.000455
105 mins	Conc N as NH3	mg/L	10	5.6	90.4
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00005	0.000028	0.000452
120 mins	Conc N as NH3	mg/L	8.38	2.37	86.2
	Vol. sample	L	0.71	0.71	0.71
	Ammount of N in feed	g	0.0059498	0.0016827	0.061202
	TOTAL N AT END	g	**1.58**	**1.35**	**1.35**
	Mass N remain in soln (g)		**0.01**	**0.00**	**0.06**
	Mass in fines + filter (g)		**0.33**	**0.15**	**0.28**
	Mass N in uptake pellets (g)		**1.24**	**1.19**	**1.00**
	Mass N lost during sampling (g)		**0.00**	**0.00**	**0.00**
	DIFFERENCE	g	**-0.23**	**-0.39**	**-0.04**
	Reduction of mass in solution		0.22	0.21	0.17
	RECOVERY (%)		**117**	**141**	**103**

Table B. 4 2009 nitrogen balance 160°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc N as NH3	**mg/L**	69.8	58.4	75.1
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50030	49990
	Amount of N in roasted struvite	**mg**	872.50	730.44	938.56
	Amount of N in roasted struvite	**g**	0.87	0.73	0.94
	Feed				
	Conc N as NH3	**mg/L**	301	298	326
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of N in feed	**mg**	225.75	223.5	245
	Amount of N in feed	**g**	0.22575	0.2235	0.24
	Total N to start	**g**	**1.10**	**0.95**	**1.18**
	Proportion of Mass N in feed		0.2055543	0.234291956	0.206667063
	Proportion of N in calcinated pellets		0.7944457	0.765708044	0.793332937
	END				
	Uptake: struvite				
	Conc N as NH3	**mg/L**	60.4	49.1	51
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	66280	72370	73050
	Amount of N in struvite after uptake	**mg**	1000.83	888.34	931.39
	Amount of N in struvite after uptake	**g**	1.00	0.89	0.93
	Fines				
	Conc N as NH3	**mg/L**	168	207	188
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	5830	3140	3250
	Amount of N in fines	**mg**	244.86	162.50	152.75
	Amount of N in fines	**g**	0.24	0.16	0.15
	Filter Paper				
	Conc N as NH3	**mg/L**	187	63.5	249
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of N on filter paper	**mg**	9.35	3.18	12.45
	Amount of N in filter paper	**g**	0.01	0.00	0.01
	Feed				
0 mins	Conc N as NH3	**mg/L**	325	216	261
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.001625	0.00108	0.001305

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc N as NH3	mg/L	137	124	130
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000685	0.00062	0.00065
30 mins	Conc N as NH3	mg/L	47.5	94	115
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0002375	0.00047	0.000575
45 mins	Conc N as NH3	mg/L	20.2	67.6	128
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000101	0.000338	0.00064
60 mins	Conc N as NH3	mg/L	12.5	51.2	113
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0000625	0.000256	0.000565
75 mins	Conc N as NH3	mg/L	8.93	39.7	95.9
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	4.465E-05	0.0001985	0.0004795
90 mins	Conc N as NH3	mg/L	6.22	32.2	99
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0000311	0.000161	0.000495
105 mins	Conc N as NH3	mg/L	6.41	23.3	94.2
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	3.205E-05	0.0001165	0.000471
120 mins	Conc N as NH3	mg/L	6.24	7.27	88.8
	Vol. sample	L	0.71	0.71	0.71
	Ammount of N in feed	g	0.0044304	0.0051617	0.063048
	TOTAL N AT END	**g**	**1.26**	**1.06**	**1.16**
	Mass N remain in soln (g)		**0.00**	**0.01**	**0.06**
	Mass in fines + filter (g)		**0.25**	**0.17**	**0.17**
	Mass N in uptake pellets (g)		**1.00**	**0.89**	**0.93**
	Mass N lost during sampling (g)		**0.00**	**0.00**	**0.01**
	DIFFERENCE	**g**	**-0.16**	**-0.11**	**0.02**
	Reduction of mass in solution		0.22	0.22	0.18
	RECOVERY (%)		**115**	**111**	**98**

Table B. 5 2009 nitrogen balance 180°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc N as NH3	mg/L	56.2	53.6	83.7
	Vol. sample	L	0.05	0.05	0.05
	Wt sample for digesting	mg	200	200	200
	Wt struvite for uptake	mg	50000	49990	50010
	Amount of N in roasted struvite	mg	702.50	669.87	1046.46
	Amount of N in roasted struvite	g	0.70	0.67	1.05
	Feed				
	Conc N as NH3	mg/L	293	290	332
	Vol. sample	L	0.75	0.75	0.75
	Amount of N in feed	mg	219.75	217.5	249
	Amount of N in feed	g	0.21975	0.2175	0.25
	Total N to start	**g**	**0.9223**	**0.8874**	**1.2955**
	Proportion of Mass N in feed		0.238276	0.24510743	0.192209828
	Proportion of N in calcinated pellets		0.761724	0.75489257	0.807790172
	END				
	Uptake: struvite				
	Conc N as NH3	mg/L	45.2	55.7	51.3
	Vol. sample	L	0.05	0.05	0.05
	Wt sample for digesting	mg	200	200	200
	Wt struvite after uptake	mg	56710	66720	63760
	Amount of N in struvite after uptake	mg	640.82	929.08	817.72
	Amount of N in struvite after uptake	g	0.64	0.93	0.82
	Fines				
	Conc N as NH3	mg/L	155	224	160
	Vol. sample	L	0.05	0.05	0.05
	Wt sample for digesting	mg	200	200	200
	Wt fines	mg	8740	4100	4930
	Amount of N in fines	mg	338.68	229.60	197.20
	Amount of N in fines	g	0.34	0.23	0.20
	Filter Paper				
	Conc N as NH3	mg/L	130	81.5	169
	Vol. sample	L	0.05	0.05	0.05
	Amount of N on filter paper	mg	6.50	4.08	8.45
	Amount of N in filter paper	g	0.01	0.00	0.01
	Feed				
0 mins	Conc N as NH3	mg/L	323	216	294
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.001615	0.00108	0.00147
15 mins	Conc N as NH3	mg/L	170	113	224

	Sample	Unit	pH 8	pH 9	pH 10
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00085	0.000565	0.00112
30 mins	Conc N as NH3	mg/L	56.2	66.1	198
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000281	0.0003305	0.00099
45 mins	Conc N as NH3	mg/L	15.9	50.7	182
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0000795	0.0002535	0.00091
60 mins	Conc N as NH3	mg/L	5.43	32.4	163
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	2.715E-05	0.000162	0.000815
75 mins	Conc N as NH3	mg/L	5.36	16.9	174
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0000268	0.0000845	0.00087
90 mins	Conc N as NH3	mg/L	3.7	8.6	164
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0000185	0.000043	0.00082
105 mins	Conc N as NH3	mg/L	5.3	4.21	153
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0000265	0.00002105	0.000765
120 mins	Conc N as NH3	mg/L	6.48	4.54	159
	Vol. sample	L	0.71	0.71	0.71
	Ammount of N in feed	g	0.0046008	0.0032234	0.11289
	TOTAL N AT END	**g**	**0.99**	**1.17**	**1.14**
	Mass N remain in soln (g)		**0.00**	**0.00**	**0.11**
	Mass in fines + filter (g)		**0.35**	**0.23**	**0.21**
	Mass N in uptake pellets (g)		**0.64**	**0.93**	**0.82**
	Mass N lost during sampling (g)		**0.00**	**0.00**	**0.01**
	DIFFERENCE	**g**	**-0.07**	**-0.28**	**0.15**
	Reduction of mass in solution		0.21	0.21	0.13
	RECOVERY (%)		**108**	**132**	**88**

Table B. 6 2009 nitrogen balance 200°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc N as NH3	**mg/L**	45.4	46.6	49.9
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50010	50020
	Amount of N in roasted struvite	**mg**	567.50	582.62	624.00
	Amount of N in roasted struvite	**g**	0.57	0.58	0.62
	Feed				
	Conc N as NH3	**mg/L**	298	321	317
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of N in feed	**mg**	223.5	240.75	238
	Amount of N in feed	**g**	0.2235	0.24075	0.24
	Total N to start	**g**	**0.79**	**0.82**	**0.86**
	Proportion of Mass N in feed		0.2825537	0.292397128	0.27589224
	Proportion of N in calcinated pellets		0.7174463	0.707602872	0.72410776
	END				
	Uptake: struvite				
	Conc N as NH3	**mg/L**	37.5	34.7	37.4
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	55400	68170	67560
	Amount of N in struvite after uptake	**mg**	519.38	591.37	631.69
	Amount of N in struvite after uptake	**g**	0.52	0.59	0.63
	Fines				
	Conc N as NH3	**mg/L**	172	202	193
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	7000	2640	2030
	Amount of N in fines	**mg**	301.00	133.32	97.95
	Amount of N in fines	**g**	0.30	0.13	0.10
	Filter Paper				
	Conc N as NH3	**mg/L**	167	54.7	61.1
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of N on filter paper	**mg**	8.35	2.74	3.06
	Amount of N in filter paper	**g**	0.01	0.00	0.00
	Feed				
0 mins	Conc N as NH3	**mg/L**	325	298	259
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.001625	0.00149	0.001295

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc N as NH3	mg/L	226	143	231
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00113	0.000715	0.001155
30 mins	Conc N as NH3	mg/L	152	111	197
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.00076	0.000555	0.000985
45 mins	Conc N as NH3	mg/L	58.5	103	181
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0002925	0.000515	0.000905
60 mins	Conc N as NH3	mg/L	40.3	81.4	184
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.0002015	0.000407	0.00092
75 mins	Conc N as NH3	mg/L	14.4	72.1	163
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	0.000072	0.0003605	0.000815
90 mins	Conc N as NH3	mg/L	6.81	55.2	166
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	3.405E-05	0.000276	0.00083
105 mins	Conc N as NH3	mg/L	6.11	56.8	169
	Vol. sample	L	0.005	0.005	0.005
	Ammount of N in feed	g	3.055E-05	0.000284	0.000845
120 mins	Conc N as NH3	mg/L	5.06	55.4	164
	Vol. sample	L	0.71	0.71	0.71
	Ammount of N in feed	g	0.0035926	0.039334	0.11644

TOTAL N AT END	**g**	**0.84**	**0.77**	**0.86**
Mass N remain in soln (g)		**0.00**	**0.04**	**0.12**
Mass in fines + filter (g)		**0.31**	**0.14**	**0.10**
Mass N in uptake pellets (g)		**0.52**	**0.59**	**0.63**
Mass N lost during sampling (g)		**0.00**	**0.00**	**0.01**
DIFFERENCE	**g**	**-0.05**	**0.05**	**0.00**
Reduction of mass in solution		0.22	0.20	0.11
RECOVERY (%)		**106**	**94**	**99**

Table B. 7 2009 phosphorus balance 100°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc P as PO4	**mg/L**	846	930	839
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50040	49990
	Amount of P in roasted struvite	**mg**	10575.00	11634.30	10485.40
	Amount of P in roasted struvite	**g**	10.58	11.63	10.49
	Feed				
	Conc P as PO4	**mg/L**	21.5	10.4	36.3
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of P in feed	**mg**	16.125	7.8	27
	Amount of P in feed	**g**	0.016125	0.0078	0.03
	Total P to start	**g**	**10.59**	**11.64**	**10.51**
	Proportion of Mass P in feed		0.0015225	0.000669982	0.002589743
	Proportion of P in calcinated pellets		0.9984775	0.999330018	0.997410257
	END				
	Uptake: struvite				
	Conc P as PO4	**mg/L**	586	527	607
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	73910	76180	72690
	Amount of P in struvite after uptake	**mg**	10827.82	10036.72	11030.71
	Amount of P in struvite after uptake	**g**	10.83	10.04	11.03
	Fines				
	Conc P as PO4	**mg/L**	561	538	570
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	2610	1490	1540
	Amount of P in fines	**mg**	366.05	200.41	219.45
	Amount of P in fines	**g**	0.37	0.20	0.22
	Filter Paper				
	Conc P as PO4	**mg/L**	156	95.8	84.5
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	7.80	4.79	4.23
	Amount of P in filter paper	**g**	0.01	0.00	0.00
	Feed				
0 mins	Conc P as PO4	**mg/L**	80.7	69.9	96.4
	Vol. sample	**L**	0.005	0.005	0.005

	Sample	Unit	pH 8	pH 9	pH 10
	Ammount of P in feed	g	0.0004035	0.0003495	0.000482
15 mins	Conc P as PO4	mg/L	107	81.3	107
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000535	0.0004065	0.000535
30 mins	Conc P as PO4	mg/L	130	83.7	108
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00065	0.0004185	0.00054
45 mins	Conc P as PO4	mg/L	154	84.3	114
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00077	0.0004215	0.00057
60 mins	Conc P as PO4	mg/L	177	89	110
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000885	0.000445	0.00055
75 mins	Conc P as PO4	mg/L	203	90.8	100
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001015	0.000454	0.0005
90 mins	Conc P as PO4	mg/L	225	93	110
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001125	0.000465	0.00055
105 mins	Conc P as PO4	mg/L	260	97.4	111
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.0013	0.000487	0.000555
120 mins	Conc P as PO4	mg/L	251	98.6	105
	Vol. sample	L	0.71	0.71	0.71
	Ammount of P in feed	g	0.17821	0.070006	0.07455
	TOTAL P AT END	g	**11.39**	**10.32**	**11.33**
	Mass P remain in soln (g)		**0.18**	**0.07**	**0.07**
	Mass in fines + filter (g)		**0.37**	**0.21**	**0.22**
	Mass P in uptake pellets (g)		**10.83**	**10.04**	**11.03**
	Mass P lost during sampling (g)		**0.01**	**0.00**	**0.00**
	DIFFERENCE	g	**-0.80**	**1.33**	**-0.82**
	Reduction of mass in solution		-0.17	-0.07	-0.05
	RECOVERY (%)		**108**	**89**	**108**

Table B. 8 2009 phosphorus balance 120°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc P as PO4	**mg/L**	908	763	796
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50030	49990
	Amount of P in roasted struvite	**mg**	11350.00	9543.22	9948.01
	Amount of P in roasted struvite	**g**	11.35	9.54	9.95
	Feed				
	Conc P as PO4	**mg/L**	15.6	9.09	10.9
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of P in feed	**mg**	11.7	6.8175	8
	Amount of P in feed	**g**	0.0117	0.0068175	0.01
	Total P to start	**g**	**11.36**	**9.55**	**9.96**
	Proportion of Mass P in feed		0.0010298	0.000713871	0.000821098
	Proportion of P in calcinated pellets		0.9989702	0.999286129	0.999178902
	END				
	Uptake: struvite				
	Conc P as PO4	**mg/L**	565	443	572
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	71070	76670	78760
	Amount of P in struvite after uptake	**mg**	10038.64	8491.20	11262.68
	Amount of P in struvite after uptake	**g**	10.04	8.49	11.26
	Fines				
	Conc P as PO4	**mg/L**	533	506	552
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	3670	2010	1850
	Amount of P in fines	**mg**	489.03	254.27	255.30
	Amount of P in fines	**g**	0.49	0.25	0.26
	Filter Paper				
	Conc P as PO4	**mg/L**	169	123	136
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	8.45	6.15	6.80
	Amount of P in filter paper	**g**	0.01	0.01	0.01
	Feed				
0 mins	Conc P as PO4	**mg/L**	10.7	115	72.2
	Vol. sample	**L**	0.005	0.005	0.005

	Sample	Unit	pH 8	pH 9	pH 10
	Ammount of P in feed	g	0.0000535	0.000575	0.000361
15 mins	Conc P as PO4	mg/L	104	132	84
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00052	0.00066	0.00042
30 mins	Conc P as PO4	mg/L	132	134	87.1
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00066	0.00067	0.0004355
45 mins	Conc P as PO4	mg/L	151	137	83.8
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000755	0.000685	0.000419
60 mins	Conc P as PO4	mg/L	181	138	84.9
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000905	0.00069	0.0004245
75 mins	Conc P as PO4	mg/L	200	141	91
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001	0.000705	0.000455
90 mins	Conc P as PO4	mg/L	235	143	88.8
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001175	0.000715	0.000444
105 mins	Conc P as PO4	mg/L	264	149	94.8
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00132	0.000745	0.000474
120 mins	Conc P as PO4	mg/L	281	151	98
	Vol. sample	L	0.71	0.71	0.71
	Ammount of P in feed	g	0.19951	0.10721	0.06958
	TOTAL P AT END	g	**10.74**	**8.86**	**11.60**
	Mass P remain in soln (g)		**0.20**	**0.11**	**0.07**
	Mass in fines + filter (g)		**0.50**	**0.26**	**0.26**
	Mass P in uptake pellets (g)		**10.04**	**8.49**	**11.26**
	Mass P lost during sampling (g)		**0.01**	**0.01**	**0.00**
	DIFFERENCE	g	**0.62**	**0.69**	**-1.64**
	Reduction of mass in solution		-0.19	-0.11	-0.06
	RECOVERY (%)		**95**	**93**	**116**

Table B. 9 2009 phosphorus balance 140°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc P as PO4	**mg/L**	739	608	834
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50000	50010
	Amount of P in roasted struvite	**mg**	9237.50	7600.00	10427.09
	Amount of P in roasted struvite	**g**	9.24	7.60	10.43
	Feed				
	Conc P as PO4	**mg/L**	20.1	11.2	13.9
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of P in feed	**mg**	15.075	8.4	10
	Amount of P in feed	**g**	0.015075	0.0084	0.01
	Total P to start	**g**	**9.25**	**7.61**	**10.44**
	Proportion of Mass P in feed		0.0016293	0.001104043	0.000998801
	Proportion of P in calcinated pellets		0.9983707	0.998895957	0.999001199
	END				
	Uptake: struvite				
	Conc P as PO4	**mg/L**	590	526	517
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	66950	71010	78250
	Amount of P in struvite after uptake	**mg**	9875.13	9337.82	10113.81
	Amount of P in struvite after uptake	**g**	9.88	9.34	10.11
	Fines				
	Conc P as PO4	**mg/L**	533	445	531
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	6170	4140	4380
	Amount of P in fines	**mg**	822.15	460.58	581.45
	Amount of P in fines	**g**	0.82	0.46	0.58
	Filter Paper				
	Conc P as PO4	**mg/L**	258	191	193
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	12.90	9.55	9.65
	Amount of P in filter paper	**g**	0.01	0.01	0.01
	Feed				
0 mins	Conc P as PO4	**mg/L**	12.4	101	123
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000062	0.000505	0.000615

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc P as PO4	mg/L	157	115	132
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000785	0.000575	0.00066
30 mins	Conc P as PO4	mg/L	244	113	133
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00122	0.000565	0.000665
45 mins	Conc P as PO4	mg/L	238	119	137
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00119	0.000595	0.000685
60 mins	Conc P as PO4	mg/L	251	128	123
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001255	0.00064	0.000615
75 mins	Conc P as PO4	mg/L	279	135	125
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001395	0.000675	0.000625
90 mins	Conc P as PO4	mg/L	297	150	127
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001485	0.00075	0.000635
105 mins	Conc P as PO4	mg/L	377	174	144
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001885	0.00087	0.00072
120 mins	Conc P as PO4	mg/L	392	229	141
	Vol. sample	L	0.71	0.71	0.71
	Ammount of P in feed	g	0.27832	0.16259	0.10011
	TOTAL P AT END	**g**	**11.00**	**9.98**	**10.81**
	Mass P remain in soln (g)		**0.28**	**0.16**	**0.10**
	Mass in fines + filter (g)		**0.84**	**0.47**	**0.59**
	Mass P in uptake pellets (g)		**9.88**	**9.34**	**10.11**
	Mass P lost during sampling (g)		**0.01**	**0.01**	**0.01**
	DIFFERENCE	**g**	**-1.75**	**-2.37**	**-0.37**
	Reduction of mass in solution		-0.27	-0.16	-0.09
	RECOVERY (%)		**119**	**131**	**104**

Table B. 10 2009 phosphorus balance 160°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc P as PO4	**mg/L**	680	577	724
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50030	49990
	Amount of P in roasted struvite	**mg**	8500.00	7216.83	9048.19
	Amount of P in roasted struvite	**g**	8.50	7.22	9.05
	Feed				
	Conc P as PO4	**mg/L**	27.7	11.8	13.7
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of P in feed	**mg**	20.775	8.85	10
	Amount of P in feed	**g**	0.020775	0.00885	0.01
	Total P to start	**g**	**8.52**	**7.23**	**9.06**
	Proportion of Mass P in feed		0.0024382	0.001224799	0.001134298
	Proportion of P in calcinated pellets		0.9975618	0.998775201	0.998865702
	END				
	Uptake: struvite				
	Conc P as PO4	**mg/L**	535	448	484
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	66280	72370	73050
	Amount of P in struvite after uptake	**mg**	8864.95	8105.44	8839.05
	Amount of P in struvite after uptake	**g**	8.86	8.11	8.84
	Fines				
	Conc P as PO4	**mg/L**	488	508	485
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	5830	3140	3250
	Amount of P in fines	**mg**	711.26	398.78	394.06
	Amount of P in fines	**g**	0.71	0.40	0.39
	Filter Paper				
	Conc P as PO4	**mg/L**	485	170	556
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	24.25	8.50	27.80
	Amount of P in filter paper	**g**	0.02	0.01	0.03
	Feed				
0 mins	Conc P as PO4	**mg/L**	19.8	104	100
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000099	0.00052	0.0005

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc P as PO4	mg/L	200	128	128
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001	0.00064	0.00064
30 mins	Conc P as PO4	mg/L	246	128	126
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00123	0.00064	0.00063
45 mins	Conc P as PO4	mg/L	282	126	120
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00141	0.00063	0.0006
60 mins	Conc P as PO4	mg/L	339	136	116
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001695	0.00068	0.00058
75 mins	Conc P as PO4	mg/L	371	139	112
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001855	0.000695	0.00056
90 mins	Conc P as PO4	mg/L	383	145	107
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001915	0.000725	0.000535
105 mins	Conc P as PO4	mg/L	410	164	109
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00205	0.00082	0.000545
120 mins	Conc P as PO4	mg/L	412	197	103
	Vol. sample	L	0.71	0.71	0.71
	Ammount of P in feed	g	0.29252	0.13987	0.07313

TOTAL P AT END	**g**	**9.90**	**8.66**	**9.34**
Mass P remain in soln (g)		**0.29**	**0.14**	**0.07**
Mass in fines + filter (g)		**0.74**	**0.41**	**0.42**
Mass P in uptake pellets (g)		**8.86**	**8.11**	**8.84**
Mass P lost during sampling (g)		**0.01**	**0.01**	**0.00**
DIFFERENCE	**g**	**-1.38**	**-1.43**	**-0.28**
Reduction of mass in solution		-0.28	-0.14	-0.07
RECOVERY (%)		**116**	**120**	**103**

Table B. 11 2009 phosphorus balance 180°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc P as PO4	**mg/L**	577	561	687
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	49990	50010
	Amount of P in roasted struvite	**mg**	7212.50	7011.10	8589.22
	Amount of P in roasted struvite	**g**	7.21	7.01	8.59
	Feed				
	Conc P as PO4	**mg/L**	22.5	14.4	12
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of P in feed	**mg**	16.875	10.8	9
	Amount of P in feed	**g**	0.016875	0.0108	0.01
	Total P to start	**g**	**7.2294**	**7.0219**	**8.5982**
	Proportion of Mass P in feed		0.0023342	0.001538046	0.001046729
	Proportion of P in calcinated pellets		0.9976658	0.998461954	0.998953271
	END				
	Uptake: struvite				
	Conc P as PO4	**mg/L**	435	466	462
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	56710	66720	63760
	Amount of P in struvite after uptake	**mg**	6167.21	7772.88	7364.28
	Amount of P in struvite after uptake	**g**	6.17	7.77	7.36
	Fines				
	Conc P as PO4	**mg/L**	462	558	478
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	8740	4100	4930
	Amount of P in fines	**mg**	1009.47	571.95	589.14
	Amount of P in fines	**g**	1.01	0.57	0.59
	Filter Paper				
	Conc P as PO4	**mg/L**	325	167	172
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	16.25	8.35	8.60
	Amount of P in filter paper	**g**	0.02	0.01	0.01
	Feed				
0 mins	Conc P as PO4	**mg/L**	13.2	90.7	51
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000066	0.0004535	0.000255

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc P as PO4	mg/L	208	138	43.2
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00104	0.00069	0.000216
30 mins	Conc P as PO4	mg/L	261	151	38.5
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001305	0.000755	0.0001925
45 mins	Conc P as PO4	mg/L	366	155	32.9
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00183	0.000775	0.0001645
60 mins	Conc P as PO4	mg/L	390	164	30.5
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00195	0.00082	0.0001525
75 mins	Conc P as PO4	mg/L	443	169	27.5
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.002215	0.000845	0.0001375
90 mins	Conc P as PO4	mg/L	466	207	25.9
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00233	0.001035	0.0001295
105 mins	Conc P as PO4	mg/L	442	219	24.4
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00221	0.001095	0.000122
120 mins	Conc P as PO4	mg/L	432	254	21.1
	Vol. sample	L	0.71	0.71	0.71
	Ammount of P in feed	g	0.30672	0.18034	0.014981
	TOTAL P AT END	**g**	**7.51**	**8.54**	**7.98**
	Mass P remain in soln (g)		**0.31**	**0.18**	**0.01**
	Mass in fines + filter (g)		**1.03**	**0.58**	**0.60**
	Mass P in uptake pellets (g)		**6.17**	**7.77**	**7.36**
	Mass P lost during sampling (g)		**0.01**	**0.01**	**0.00**
	DIFFERENCE	**g**	**-0.28**	**-1.52**	**0.62**
	Reduction of mass in solution		-0.30	-0.18	-0.01
	RECOVERY (%)		**104**	**122**	**93**

Table B. 12 2009 phosphorus balance 200°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc P as PO4	**mg/L**	511	559	564
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50010	50020
	Amount of P in roasted struvite	**mg**	6387.50	6988.90	7052.82
	Amount of P in roasted struvite	**g**	6.39	6.99	7.05
	Feed				
	Conc P as PO4	**mg/L**	24	12	11.6
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of P in feed	**mg**	18	9	9
	Amount of P in feed	**g**	0.018	0.009	0.01
	Total P to start	**g**	**6.41**	**7.00**	**7.06**
	Proportion of Mass P in feed		0.0028101	0.00128601	0.00123202
	Proportion of P in calcinated pellets		0.9971899	0.99871389	0.99876797
	END				
	Uptake: struvite				
	Conc P as PO4	**mg/L**	366	391	373
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	55400	68170	67560
	Amount of P in struvite after uptake	**mg**	5069.10	6663.62	6299.97
	Amount of P in struvite after uptake	**g**	5.07	6.66	6.30
	Fines				
	Conc P as PO4	**mg/L**	460	493	469
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	7000	2640	2030
	Amount of P in fines	**mg**	805.00	325.38	238.02
	Amount of P in fines	**g**	0.81	0.33	0.24
	Filter Paper				
	Conc P as PO4	**mg/L**	390	118	130
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	19.50	5.90	6.50
	Amount of P in filter paper	**g**	0.02	0.01	0.01
	Feed				
0 mins	Conc P as PO4	**mg/L**	14.3	134	39
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000071	0.00067	0.000195

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc P as PO4	mg/L	183	82.5	51.3
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000915	0.0004125	0.0002565
30 mins	Conc P as PO4	mg/L	193	95.5	16.6
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.000965	0.0004775	0.000083
45 mins	Conc P as PO4	mg/L	227	96.1	13
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.001135	0.0004805	0.000065
60 mins	Conc P as PO4	mg/L	268	95.2	10.9
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00134	0.000476	0.0000545
75 mins	Conc P as PO4	mg/L	288	97.1	10.9
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00144	0.0004855	0.0000545
90 mins	Conc P as PO4	mg/L	354	95.1	10.4
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00177	0.0004755	0.000052
105 mins	Conc P as PO4	mg/L	374	93.1	9.35
	Vol. sample	L	0.005	0.005	0.005
	Ammount of P in feed	g	0.00187	0.0004655	0.00004675
120 mins	Conc P as PO4	mg/L	369	93.6	9.44
	Vol. sample	L	0.71	0.71	0.71
	Ammount of P in feed	g	0.26199	0.066456	0.0067024
	TOTAL P AT END	**g**	**6.17**	**7.07**	**6.55**
	Mass P remain in soln (g)		**0.26**	**0.07**	**0.01**
	Mass in fines + filter (g)		**0.82**	**0.33**	**0.24**
	Mass P in uptake pellets (g)		**5.07**	**6.66**	**6.30**
	Mass P lost during sampling (g)		**0.01**	**0.00**	**0.00**
	DIFFERENCE	**g**	**0.24**	**-0.07**	**0.51**
	Reduction of mass in solution		-0.25	-0.06	0.00
	RECOVERY (%)		**96**	**101**	**93**

Table B. 13 2009 magnesium balance 100°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc Mg	**mg/L**	558.125	534.595	445.265
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50040	49990
	Amount of Mg in roasted struvite	**mg**	6976.56	6687.78	5564.70
	Amount of Mg in roasted struvite	**g**	6.98	6.69	5.56
	Feed				
	Conc Mg	**mg/L**	2.5635	28.323	30.62
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of Mg in feed	**mg**	1.922625	21.24225	23
	Amount of Mg in feed	**g**	0.001922 6	0.02124225	0.02
	Total Mg to start	**g**	**6.98**	**6.71**	**5.59**
	Proportion of Mass Mg in feed		0.000275 5	0.00316622	0.00410994 6
	Proportion of Mg in calcinated pellets		0.999724 5	0.99683378	0.99589005 4
	END				
	Uptake: struvite				
	Conc Mg	**mg/L**	377.82	338.585	336.215
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	73910	76180	72690
	Amount of Mg in struvite after uptake	**mg**	6981.17	6448.35	6109.87
	Amount of Mg in struvite after uptake	**g**	6.98	6.45	6.11
	Fines				
	Conc Mg	**mg/L**	355.68	400.205	409.135
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	2610	1490	1540
	Amount of Mg in fines	**mg**	232.08	149.08	157.52
	Amount of Mg in fines	**g**	0.23	0.15	0.16
	Filter Paper				
	Conc Mg	**mg/L**	97.555	54.902	62.6125
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of Mg on filter paper	**mg**	4.88	2.75	3.13
	Amount of Mg in filter paper	**g**	0.00	0.00	0.00
	Feed				
0 mins	Conc Mg	**mg/L**	10.334	5.369	2.3755
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	5.167E-05	0.00002684 5	1.18775E-05

	Sample	Unit	pH 8	pH 9	pH 10
15 mins	Conc Mg	mg/L	7.1505	2.0095	2.13
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	3.575E-05	1.00475E-05	0.00001065
30 mins	Conc Mg	mg/L	4.4105	2.1565	1.706
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	2.205E-05	1.07825E-05	0.00000853
45 mins	Conc Mg	mg/L	3.025	1.8325	1.6275
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	1.513E-05	9.1625E-06	8.1375E-06
60 mins	Conc Mg	mg/L	5.5465	2.59	1.7675
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	2.773E-05	0.00001295	8.8375E-06
75 mins	Conc Mg	mg/L	1.729	2.4095	1.9055
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	8.645E-06	1.20475E-05	9.5275E-06
90 mins	Conc Mg	mg/L	26.411	1.928	2.031
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0001321	0.00000964	0.000010155
105 mins	Conc Mg	mg/L	14.8145	1.8995	1.3155
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	7.407E-05	9.4975E-06	6.5775E-06
120 mins	Conc Mg	mg/L	6.116	1.9635	1.883
	Vol. sample	L	0.71	0.71	0.71
	Ammount of Mg in feed	g	0.0043424	0.001394085	0.00133693
	TOTAL Mg AT END	**g**	**7.22**	**6.60**	**6.27**
	Mass Mg remain in soln (g)		**0.00**	**0.00**	**0.00**
	Mass in fines + filter (g)		**0.24**	**0.15**	**0.16**
	Mass Mg in uptake pellets (g)		**6.98**	**6.45**	**6.11**
	Mass Mg lost during sampling (g)		**0.00**	**0.00**	**0.00**
	DIFFERENCE	**g**	**-0.24**	**0.11**	**-0.68**
	Reduction of mass in solution		0.00	0.02	0.02
	RECOVERY (%)		**104**	**98**	**112**

Table B. 14 2009 magnesium balance 120°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc Mg	**mg/L**	528.945	550.155	600.42
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50030	49990
	Amount of Mg in roasted struvite	**mg**	6611.81	6881.06	7503.75
	Amount of Mg in roasted struvite	**g**	6.61	6.88	7.50
	Feed				
	Conc Mg	**mg/L**	3.4015	26.1955	35.143
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of Mg in feed	**mg**	2.551125	19.646625	26
	Amount of Mg in feed	**g**	0.0025511	0.019646625	0.03
	Total Mg to start	**g**	**6.61**	**6.90**	**7.53**
	Proportion of Mass Mg in feed		0.0003857	0.002847044	0.003500249
	Proportion of Mg in calcinated pellets		0.9996143	0.997152956	0.996499751
	END				
	Uptake: struvite				
	Conc Mg	**mg/L**	426.26	356.305	330.615
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	71070	76670	78760
	Amount of Mg in struvite after uptake	**mg**	7573.57	6829.48	6509.81
	Amount of Mg in struvite after uptake	**g**	7.57	6.83	6.51
	Fines				
	Conc Mg	**mg/L**	331.725	392.72	387.22
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	3670	2010	1850
	Amount of Mg in fines	**mg**	304.36	197.34	179.09
	Amount of Mg in fines	**g**	0.30	0.20	0.18
	Filter Paper				
	Conc Mg	**mg/L**	35.575	79.6695	227.495
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of Mg on filter paper	**mg**	1.78	3.98	11.37
	Amount of Mg in filter paper	**g**	0.00	0.00	0.01
	Feed				
0 mins	Conc Mg	**mg/L**	3.6065	5.661	3.9515
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	1.803E-05	0.000028305	1.97575E-05
15 mins	Conc Mg	**mg/L**	3.224	7.218	2.346
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	1.612E-05	0.00003609	0.00001173

	Sample	Unit	pH 8	pH 9	pH 10
30 mins	Conc Mg	mg/L	1.2475	5.146	2.793
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	6.238E-06	0.00002573	0.000013965
45 mins	Conc Mg	mg/L	2.173	3.831	3.2175
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	1.087E-05	0.000019155	1.60875E-05
60 mins	Conc Mg	mg/L	2.173	4.188	3.226
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	1.087E-05	0.00002094	0.00001613
75 mins	Conc Mg	mg/L	7.9105	4.175	3.2005
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	3.955E-05	0.000020875	1.60025E-05
90 mins	Conc Mg	mg/L	14.056	4.0325	3.1655
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	7.028E-05	2.01625E-05	1.58275E-05
105 mins	Conc Mg	mg/L	25.746	4.9435	1.8175
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0001287	2.47175E-05	9.0875E-06
120 mins	Conc Mg	mg/L	5.7625	4.432	4.0565
	Vol. sample	L	0.71	0.71	0.71
	Ammount of Mg in feed	g	0.0040914	0.00314672	0.002880115
	TOTAL Mg AT END	g	**7.88**	**7.03**	**6.70**
	Mass Mg remain in soln (g)		**0.00**	**0.00**	**0.00**
	Mass in fines + filter (g)		**0.31**	**0.20**	**0.19**
	Mass Mg in uptake pellets (g)		**7.57**	**6.83**	**6.51**
	Mass Mg lost during sampling (g)		**0.00**	**0.00**	**0.00**
	DIFFERENCE	g	**-1.27**	**-0.13**	**0.83**
	Reduction of mass in solution		0.00	0.02	0.02
	RECOVERY (%)		**119**	**102**	**89**

Table B. 15 2009 magnesium balance 140°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc Mg	**mg/L**	507.745	460.25	526.545
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50000	50010
	Amount of Mg in roasted struvite	**mg**	6346.81	5753.13	6583.13
	Amount of Mg in roasted struvite	**g**	6.35	5.75	6.58
	Feed				
	Conc Mg	**mg/L**	6.7985	28.5885	27.5075
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of Mg in feed	**mg**	5.098875	21.441375	21
	Amount of Mg in feed	**g**	0.0050989	0.021441375	0.02
	Total Mg to start	**g**	**6.35**	**5.77**	**6.60**
	Proportion of Mass Mg in feed		0.0008027	0.003713071	0.003124073
	Proportion of Mg in calcinated pellets		0.9991973	0.996286929	0.996875927
	END				
	Uptake: struvite				
	Conc Mg	**mg/L**	414.535	403.015	287.29
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	66950	71010	78250
	Amount of Mg in struvite after uptake	**mg**	6938.28	7154.52	5620.11
	Amount of Mg in struvite after uptake	**g**	6.94	7.15	5.62
	Fines				
	Conc Mg	**mg/L**	330.7	344.835	429.195
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	6170	4140	4380
	Amount of Mg in fines	**mg**	510.10	356.90	469.97
	Amount of Mg in fines	**g**	0.51	0.36	0.47
	Filter Paper				
	Conc Mg	**mg/L**	206.065	134.86	327.19
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of Mg on filter paper	**mg**	10.30	6.74	16.36
	Amount of Mg in filter paper	**g**	0.01	0.01	0.02
	Feed				
0 mins	Conc Mg	**mg/L**	38.706	11.859	4.6275
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0001935	0.000059295	2.31375E-05
15 mins	Conc Mg	**mg/L**	66.6185	13.1475	8.257
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0003331	6.57375E-05	0.000041285
30 mins	Conc Mg	**mg/L**	51.0805	13.3695	10.588

	Sample	Unit	pH 8	pH 9	pH 10
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0002554	6.68475E-05	0.00005294
45 mins	Conc Mg	mg/L	55.735	15.3885	11.463
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0002787	7.69425E-05	0.000057315
60 mins	Conc Mg	mg/L	68.7255	16.968	12.4735
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0003436	0.00008484	6.23675E-05
75 mins	Conc Mg	mg/L	82.277	19.1225	12.971
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0004114	9.56125E-05	0.000064855
90 mins	Conc Mg	mg/L	74.7505	24.509	13.2465
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0003738	0.000122545	6.62325E-05
105 mins	Conc Mg	mg/L	150.435	40.1565	12.5235
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0007522	0.000200783	6.26175E-05
120 mins	Conc Mg	mg/L	166.485	51.987	13.664
	Vol. sample	L	0.71	0.71	0.71
	Ammount of Mg in feed	g	0.1182044	0.03691077	0.00970144
	TOTAL Mg AT END	**g**	**7.58**	**7.56**	**6.12**
	Mass Mg remain in soln (g)		**0.12**	**0.04**	**0.01**
	Mass in fines + filter (g)		**0.52**	**0.36**	**0.49**
	Mass Mg in uptake pellets (g)		**6.94**	**7.15**	**5.62**
	Mass Mg lost during sampling (g)		**0.00**	**0.00**	**0.00**
	DIFFERENCE	**g**	**-1.23**	**-1.78**	**0.49**
	Reduction of mass in solution		-0.12	-0.02	0.01
	RECOVERY (%)		**119**	**131**	**93**

Table B. 16 2009 magnesium balance 160°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc Mg	**mg/L**	590.755	461.765	971.415
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50030	49990
	Amount of Mg in roasted struvite	**mg**	7384.44	5775.53	12140.26
	Amount of Mg in roasted struvite	**g**	7.38	5.78	12.14
	Feed				
	Conc Mg	**mg/L**	35.0835	32.135	32.4115
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of Mg in feed	**mg**	26.312625	24.10125	24
	Amount of Mg in feed	**g**	0.0263126	0.02410125	0.02
	Total Mg to start	**g**	**7.41**	**5.80**	**12.16**
	Proportion of Mass Mg in feed		0.0035506	0.004155655	0.001998314
	Proportion of Mg in calcinated pellets		0.9964494	0.995844345	0.998001686
	END				
	Uptake: struvite				
	Conc Mg	**mg/L**	436.385	377.77	389.55
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	66280	72370	73050
	Amount of Mg in struvite after uptake	**mg**	7230.90	6834.80	7114.16
	Amount of Mg in struvite after uptake	**g**	7.23	6.83	7.11
	Fines				
	Conc Mg	**mg/L**	348.38	369.735	313.235
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	5830	3140	3250
	Amount of Mg in fines	**mg**	507.76	290.24	254.50
	Amount of Mg in fines	**g**	0.51	0.29	0.25
	Filter Paper				
	Conc Mg	**mg/L**	348.28	115.81	357.06
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of Mg on filter paper	**mg**	17.41	5.79	17.85
	Amount of Mg in filter paper	**g**	0.02	0.01	0.02
	Feed				
0 mins	Conc Mg	**mg/L**	34.1185	13.064	6.4235
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0001706	0.00006532	3.21175E-05
15 mins	Conc Mg	**mg/L**	55.4185	14.612	11.5665
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0002771	0.00007306	5.78325E-05
30 mins	Conc Mg	**mg/L**	73.5385	15.296	20.2225

	Sample	Unit	pH 8	pH 9	pH 10
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0003677	0.00007648	0.000101113
45 mins	Conc Mg	mg/L	73.3185	16.84	24.2205
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0003666	0.0000842	0.000121103
60 mins	Conc Mg	mg/L	78.32	20.5585	24.8635
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0003916	0.000102793	0.000124318
75 mins	Conc Mg	mg/L	83.1175	19.958	24.075
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0004156	0.00009979	0.000120375
90 mins	Conc Mg	mg/L	90.683	21.6575	26.605
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0004534	0.000108288	0.000133025
105 mins	Conc Mg	mg/L	170.595	27.622	30.0545
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.000853	0.00013811	0.000150273
120 mins	Conc Mg	mg/L	162.905	25.5055	33.3745
	Vol. sample	L	0.71	0.71	0.71
	Ammount of Mg in feed	g	0.1156626	0.018108905	0.023695895
	TOTAL Mg AT END	g	**7.88**	**7.15**	**7.41**
	Mass Mg remain in soln (g)		**0.12**	**0.02**	**0.02**
	Mass in fines + filter (g)		**0.53**	**0.30**	**0.27**
	Mass Mg in uptake pellets (g)		**7.23**	**6.83**	**7.11**
	Mass Mg lost during sampling (g)		**0.00**	**0.00**	**0.00**
	DIFFERENCE	g	**-0.46**	**-1.35**	**4.75**
	Reduction of mass in solution		-0.09	0.01	0.00
	RECOVERY (%)		**106**	**123**	**61**

Table B. 17 2009 magnesium balance 180°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc Mg	**mg/L**	520.095	546.14	607.225
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	49990	50010
	Amount of Mg in roasted struvite	**mg**	6501.19	6825.38	7591.83
	Amount of Mg in roasted struvite	**g**	6.50	6.83	7.59
	Feed				
	Conc Mg	**mg/L**	35.81	30.6935	33.017
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of Mg in feed	**mg**	26.8575	23.020125	25
	Amount of Mg in feed	**g**	0.0268575	0.023020125	0.02
	Total Mg to start	**g**	**6.5280**	**6.8484**	**7.6166**
	Proportion of Mass Mg in feed		0.0041142	0.003361385	0.003251158
	Proportion of Mg in calcinated pellets		0.9958858	0.996638615	0.996748842
	END				
	Uptake: struvite				
	Conc Mg	**mg/L**	415.79	485.765	444.44
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	56710	66720	63760
	Amount of Mg in struvite after uptake	**mg**	5894.86	8102.56	7084.37
	Amount of Mg in struvite after uptake	**g**	5.89	8.10	7.08
	Fines				
	Conc Mg	**mg/L**	350.895	423.33	358.37
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	8740	4100	4930
	Amount of Mg in fines	**mg**	766.71	433.91	441.69
	Amount of Mg in fines	**g**	0.77	0.43	0.44
	Filter Paper				
	Conc Mg	**mg/L**	232.02	111.3	283.325
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of Mg on filter paper	**mg**	11.60	5.57	14.17
	Amount of Mg in filter paper	**g**	0.01	0.01	0.01
	Feed				
0 mins	Conc Mg	**mg/L**	38.11	18.5435	20.235
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0001906	9.27175E-05	0.000101175
15 mins	Conc Mg	**mg/L**	108.915	23.032	14.401
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0005446	0.00011516	0.000072005
30 mins	Conc Mg	**mg/L**	131.525	28.1515	20.5035

	Sample	Unit	pH 8	pH 9	pH 10
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0006576	0.000140758	0.000102518
45 mins	Conc Mg	mg/L	176.04	29.908	23.989
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0008802	0.00014954	0.000119945
60 mins	Conc Mg	mg/L	209.145	32.0055	27.116
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0010457	0.000160028	0.00013558
75 mins	Conc Mg	mg/L	242.6	34.4925	28.337
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.001213	0.000172463	0.000141685
90 mins	Conc Mg	mg/L	255.6	51.5035	31.715
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.001278	0.000257518	0.000158575
105 mins	Conc Mg	mg/L	194.6	53.9835	34.0485
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.000973	0.000269918	0.000170243
120 mins	Conc Mg	mg/L	168.02	64.385	36.3155
	Vol. sample	L	0.71	0.71	0.71
	Ammount of Mg in feed	g	0.1192942	0.04571335	0.025784005
	TOTAL Mg AT END	**g**	**6.80**	**8.59**	**7.57**
	Mass Mg remain in soln (g)		**0.12**	**0.05**	**0.03**
	Mass in fines + filter (g)		**0.78**	**0.44**	**0.46**
	Mass Mg in uptake pellets (g)		**5.89**	**8.10**	**7.08**
	Mass Mg lost during sampling (g)		**0.01**	**0.00**	**0.00**
	DIFFERENCE	**g**	**-0.27**	**-1.74**	**0.05**
	Reduction of mass in solution		-0.10	-0.02	0.00
	RECOVERY (%)		**104**	**125**	**99**

Table B. 18 2009 magnesium balance 200°C

	Sample	Unit	pH 8	pH 9	pH 10
	START				
	Roasted struvite				
	Conc Mg	**mg/L**	524.615	491.235	52.64
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite for uptake	**mg**	50000	50010	50020
	Amount of Mg in roasted struvite	**mg**	6557.69	6141.67	658.26
	Amount of Mg in roasted struvite	**g**	6.56	6.14	0.66
	Feed				
	Conc Mg	**mg/L**	40.475	29.9265	28.855
	Vol. sample	**L**	0.75	0.75	0.75
	Amount of Mg in feed	**mg**	30.35625	22.444875	22
	Amount of Mg in feed	**g**	0.0303563	0.022444875	0.02
	Total Mg to start	**g**	**6.59**	**6.16**	**0.68**
	Proportion of Mass Mg in feed		0.0046078	0.003641219	0.03182984
	Proportion of Mg in calcinated pellets		0.9953922	0.996358781	0.96817016
	END				
	Uptake: struvite				
	Conc Mg	**mg/L**	418.05	327.145	57.225
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt struvite after uptake	**mg**	55400	68170	67560
	Amount of Mg in struvite after uptake	**mg**	5789.99	5575.37	966.53
	Amount of Mg in struvite after uptake	**g**	5.79	5.58	0.97
	Fines				
	Conc Mg	**mg/L**	332.725	360.505	145.39
	Vol. sample	**L**	0.05	0.05	0.05
	Wt sample for digesting	**mg**	200	200	200
	Wt fines	**mg**	7000	2640	2030
	Amount of Mg in fines	**mg**	582.27	237.93	73.79
	Amount of Mg in fines	**g**	0.58	0.24	0.07
	Filter Paper				
	Conc Mg	**mg/L**	294.7	76.631	11.75
	Vol. sample	**L**	0.05	0.05	0.05
	Amount of Mg on filter paper	**mg**	14.74	3.83	0.59
	Amount of Mg in filter paper	**g**	0.01	0.00	0.00
	Feed				
0 mins	Conc Mg	**mg/L**	37.91	75.7965	29.112
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0001896	0.000378983	0.00014556
15 mins	Conc Mg	**mg/L**	156.54	27.3775	38.8465
	Vol. sample	**L**	0.005	0.005	0.005
	Ammount of Mg in feed	**g**	0.0007827	0.000136888	0.000194233
30 mins	Conc Mg	**mg/L**	160.205	34.8695	22.452

	Sample	Unit	pH 8	pH 9	pH 10
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.000801	0.000174348	0.00011226
45 mins	Conc Mg	mg/L	159.65	35.626	28.0095
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0007983	0.00017813	0.000140048
60 mins	Conc Mg	mg/L	183.615	36.01	32.0795
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0009181	0.00018005	0.000160398
75 mins	Conc Mg	mg/L	187.415	34.855	34.6805
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0009371	0.000174275	0.000173403
90 mins	Conc Mg	mg/L	227.17	30.58	35.553
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0011359	0.0001529	0.000177765
105 mins	Conc Mg	mg/L	226.965	30.481	39.0735
	Vol. sample	L	0.005	0.005	0.005
	Ammount of Mg in feed	g	0.0011348	0.000152405	0.000195368
120 mins	Conc Mg	mg/L	208.285	27.4405	39.129
	Vol. sample	L	0.71	0.71	0.71
	Ammount of Mg in feed	g	0.1478824	0.019482755	0.02778159
	TOTAL Mg AT END	**g**	**6.54**	**5.84**	**1.07**
	Mass Mg remain in soln (g)		**0.15**	**0.02**	**0.03**
	Mass in fines + filter (g)		**0.60**	**0.24**	**0.07**
	Mass Mg in uptake pellets (g)		**5.79**	**5.58**	**0.97**
	Mass Mg lost during sampling (g)		**0.01**	**0.00**	**0.00**
	DIFFERENCE	**g**	**0.05**	**0.33**	**-0.39**
	Reduction of mass in solution		-0.12	0.00	-0.01
	RECOVERY (%)		**99**	**95**	**157**

Table B. 19 2010 mass balance summary for N, P, and Mg

ID	Conditions	N	P	Mg
9a	Constant pH 8, 2hour, T=105, Mass=20g	94.5	107.5	96.5
9b	Constant pH 8, 2hour, T=105, Mass=20g	92.6	107.6	97.6
9c	Initial pH 8, 2hour, T=105, Mass=20g	85.7	105.4	97.2
10a	Constant pH 8, 2hour, T=105, Mass=20g	110.2	103.0	103.9
10b	Rehydration pH 8, 15min, T=105, Mass=20g	110.4	95.0	102.7
10c	Constant pH 8, 2hour, T=105, Mass=40g	102.6	102.6	101.7
11a	Constant pH 8, 2hour, T=160, Mass=20g	98.9	101.9	99.8
11b	Constant pH 8, 2hour, T=160, Mass=40g	97.8	103.7	101.0
11c	Initial pH 8, 2hour, T=160, Mass=20g	100.9	72.9	85.9
11d	Initial pH 8 filtrate, 30min, T=160, Mass=20g	95.3	91.4	110.7
12a	Constant pH 8, 2hour, T=80, Mass=20g	105.7	119.4	120.4
12b	Rehydration, 15min, T=80, Mass=5.5g	107.9	202.1	190.7
12c	Constant pH 8, 2hour, T=80, Mass=20g	103.8	114.9	119.3
12d	Constant pH 8, 2hour, T=80, Mass=40g	104.3	135.5	119.3
15a	Constant pH 9, 2hour, T=80, Mass=20g	101.1	104.2	100.9
15b	Constant pH 9, 2hour, T=80, Mass=40g	94.9	99.7	101.1
15c	Diss-ref pH 9, 2hour, T=80, Mass=20g	99.5	100.9	99.3
16a	Diss-ref pH 9, 2hour, T=160, Mass=20g	74.5	84.4	87.8
16b	Constant pH 9, 2hour, T=160, Mass=20g	102.2	98.2	100.1
16c	Constant pH 9, 2hour, T=160, Mass=40g	81.6	62.9	67.4
17a	Diss-ref pH 9, 2hour, T=105, Mass=20g	96.3	98.6	91.4
17b	Constant pH 9, 2hour, T=105, Mass=20g	112.8	100.9	165.7
17c	Constant pH 9, 2hour, T=105, Mass=40g	122.1	91.4	93.2

Table B. 20 2010 nitrogen balance 80°C

Temperature: 80°C		12a	12b	12c	12d	15a	15b	15c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START								
Roasted struvite								
Conc N as NH3	**mg/L**	5.41	5.41	5.41	5.41	4.92	4.92	4.92
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	40.7	40.7	40.7	40.7	47.3	47.3	47.3
Wt struvite for uptake	**mg**	20159.5	5489	19802.2	40048.3	20068.5	39729.1	19590
Amount of N in roasted struvite	**mg**	669.92	182.40	658.05	1330.84	521.87	1033.12	509.42
Amount of N in roasted struvite	**g**	0.67	0.18	0.66	1.33	0.52	1.03	0.51
Feed								
Conc N as NH3	**mg/L**	703	0.148	661	681	616	636	650
Vol. sample	**L**	0.5	0.5	0.5	0.5	0.5	0.5	0.577
Amount of N in feed	**mg**	351.5	0.074	331	341	308	318	375
Amount of N in feed	**g**	0.3515	0.000074	0.33	0.34	0.31	0.32	0.38
Total N to start	**g**	**1.02**	**0.18**	**0.99**	**1.67**	**0.83**	**1.35**	**0.88**
Proportion of Mass N in feed		0.34	0.00	0.33	0.20	0.37	0.24	0.42
Proportion of N in calcinated pellets		0.66	1.00	0.67	0.80	0.63	0.76	0.58
END								
Uptake: struvite								
Conc N as NH3	**mg/L**	4.47	4.15	4.43	4.33	3.35	3.21	0
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	43.9	40.2	42.8	41.8	37.4	38.8	0
Wt struvite after uptake	**mg**	30659.5	7361.8	27926.5	56265.5	24887	49176	0
Amount of N in struvite after uptake	**mg**	780.46	190.00	722.63	1457.11	557.30	1017.11	0.00
Amount of N in struvite after uptake	**g**	0.78	0.19	0.72	1.46	0.56	1.02	0.00
Fines								
Conc N as NH3	**mg/L**	8.95	0	9.36	9.49	7.58	7.41	4.65
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	39.8	0	41.6	41.9	36.3	37.4	40.3
Wt fines	**mg**	427.7	23.8	417	918.7	135.2	393.3	30001.5
Amount of N in fines	**mg**	24.04	0.00	23.46	52.02	7.06	19.48	865.43
Amount of N in fines	**g**	0.02	0.00	0.02	0.05	0.01	0.02	0.87
Filter Paper								
Conc N as NH3	**mg/L**	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Amount of N on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of N in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed								
0 mins Conc N as NH3	**mg/L**	667	0	658	663	617	639	1700
Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Ammount of N in feed	**g**	0.003335	0	0.00329	0.003315	0.003085	0.003195	0.0085

	Temperature: 80°C		12a	12b	12c	12d	15a	15b	15c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
15 mins	Conc N as NH3	**mg/L**	599	0	599	545	563	523	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.002995	0	0.002995	0.002725	0.002815	0.002615	0
30 mins	Conc N as NH3	**mg/L**	588	0	587	522	563	515	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00294	0	0.002935	0.00261	0.002815	0.002575	0
45 mins	Conc N as NH3	**mg/L**	554	0	573	495	551	512	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00277	0	0.002865	0.002475	0.002755	0.00256	0
60 mins	Conc N as NH3	**mg/L**	561	0	573	483	565	502	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.002805	0	0.002865	0.002415	0.002825	0.00251	0
75 mins	Conc N as NH3	**mg/L**	558	0	559	468	553	500	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00279	0	0.002795	0.00234	0.002765	0.0025	0
90 mins	Conc N as NH3	**mg/L**	572	0	583	476	560	500	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00286	0	0.002915	0.00238	0.0028	0.0025	0
105 mins	Conc N as NH3	**mg/L**	559	0	549	474	506	486	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.002795	0	0.002745	0.00237	0.00253	0.00243	0
120 mins	Conc N as NH3	**mg/L**	548	13.9	557	464	548	488	10.5
	Vol. sample	**L**	0.46	0.49	0.46	0.46	0.46	0.46	0.567
	Ammount of N in feed	**g**	0.25208	0.006811	0.25622	0.21344	0.25208	0.22448	0.0059535
	TOTAL N AT END	**g**	**1.08**	**0.20**	**1.03**	**1.74**	**0.84**	**1.28**	**0.88**
	Mass N remain in soln (g)		**0.25**	**0.01**	**0.26**	**0.21**	**0.25**	**0.22**	**0.01**
	Mass in fines + filter (g)		**0.02**	**0.00**	**0.02**	**0.05**	**0.01**	**0.02**	**0.87**
	Mass N in uptake pellets (g)		**0.78**	**0.19**	**0.72**	**1.46**	**0.56**	**1.02**	**0.00**
	Mass N lost during sampling (g)		**0.02**	**0.00**	**0.02**	**0.02**	**0.02**	**0.02**	**0.01**
	DIFFERENCE	**g**	**-0.06**	**-0.01**	**-0.04**	**-0.07**	**-0.01**	**0.07**	**0.00**
	Reduction of mass in solution		0.08	-0.01	0.05	0.11	0.03	0.07	0.36
	RECOVERY (%)		**106**	**108**	**104**	**104**	**101**	**95**	**99**

Table B. 21 2010 nitrogen balance 105°C

Temperature: 105°C		9a	9b	9c	10a	10b	10c	17a	17b	17c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START										
Roasted struvite										
Conc N as NH3	**mg/L**	6.91	6.91	6.91	5.04	5.04	5.04	3.03	3.03	3.03
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	41.2	41.2	41.2	38.4	38.4	38.4	35.4	35.4	35.4
Wt struvite for uptake	**mg**	20053.8	20026.6	20026	19950	19958	40551	19871	19911.7	39942.4
Amount of N in roasted struvite	**mg**	840.85	839.71	839.68	654.61	654.87	1330.58	425.21	426.08	854.70
Amount of N in roasted struvite	**g**	0.84	0.84	0.84	0.65	0.65	1.33	0.43	0.43	0.85
Feed										
Conc N as NH3	**mg/L**	578	677	680	661	3.27	663	767.5	871	939
Vol. sample	**L**	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5
Amount of N in feed	**mg**	289	338.5	340	331	2	332	461	436	470
Amount of N in feed	**g**	0.289	0.3385	0.34	0.33	0.00	0.33	0.46	0.44	0.47
Total N to start	**g**	**1.13**	**1.18**	**1.18**	**0.99**	**0.66**	**1.66**	**0.89**	**0.86**	**1.32**
Proportion of Mass N in feed		0.26	0.29	0.29	0.34	0.00	0.20	0.52	0.51	0.35
Proportion of N in calcinated pellets		0.74	0.71	0.71	0.66	1.00	0.80	0.48	0.49	0.65
END										
Uptake: struvite										
Conc N as NH3	**mg/L**	4.59	4.15	4.87	4.15	3.65	3.66	0	3.97	4.04
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	41	39.2	41.2	38.3	39.2	38.2	0	43.6	40.7
Wt struvite after uptake	**mg**	29071.2	30211.9	26399.5	30497.1	30427.8	61526.8	0	24837.8	51166.7
Amount of N in struvite after uptake	**mg**	813.64	799.61	780.13	826.13	708.30	1473.74	0.00	565.40	1269.74
Amount of N in struvite after uptake	**g**	0.81	0.80	0.78	0.83	0.71	1.47	0.00	0.57	1.27
Fines										
Conc N as NH3	**mg/L**	7.85	7.5	6.21	8.59	1.18	8.94	5.41	4.81	8.15
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	38.6	39	37.3	38	11.6	39.1	50.9	23	38.2
Wt fines	**mg**	391.2	516.7	45.8	507	34.5	1525	31605.3	120.4	234.8
Amount of N in fines	**mg**	19.89	24.84	1.91	28.65	0.88	87.17	839.81	6.29	12.52
Amount of N in fines	**g**	0.02	0.02	0.00	0.03	0.00	0.09	0.84	0.01	0.01
Filter Paper										
Conc N as NH3	**mg/L**	0	0	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05						
Amount of N on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of N in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed										
0 mins Conc N as NH3	**mg/L**	712	679	676	679	0	671	1820	868	867

	Temperature: 105°C		9a	9b	9c	10a	10b	10c	17a	17b	17c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00356	0.003395	0.00338	0.003395	0	0.003355	0.0091	0.00434	0.00434
15 mins	Conc N as NH3	**mg/L**	610	597	0	604	0	476	0	765	792
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00305	0.002985	0	0.00302	0	0.00238	0	0.00383	0.00396
30 mins	Conc N as NH3	**mg/L**	613	595	0	540	0	410	0	734	733
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.003065	0.002975	0	0.0027	0	0.00205	0	0.00367	0.00367
45 mins	Conc N as NH3	**mg/L**	570	569	0	530	0	368	0	738	655
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00285	0.002845	0	0.00265	0	0.00184	0	0.00369	0.00328
60 mins	Conc N as NH3	**mg/L**	542	537	0	521	0	342	0	814	733
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00271	0.002685	0	0.002605	0	0.00171	0	0.00407	0.00367
75 mins	Conc N as NH3	**mg/L**	519	559	0	501	0	321	0	763	693
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.002595	0.002795	0	0.002505	0	0.001605	0	0.00382	0.00347
90 mins	Conc N as NH3	**mg/L**	515	569	0	494	0	300	0	758	732
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.002575	0.002845	0	0.00247	0	0.0015	0	0.00379	0.00366
105 mins	Conc N as NH3	**mg/L**	496	561	0	466	0	286	0	772	703
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00248	0.002805	0	0.00233	0	0.00143	0	0.00386	0.00352
120 mins	Conc N as NH3	**mg/L**	460	530	490	455	32.2	279	7.43	803	662
	Vol. sample	**L**	0.46	0.46	0.46	0.46	0.49	0.46	0.56	0.46	0.46
	Ammount of N in feed	**g**	0.2116	0.2438	0.2254	0.2093	0.01578	0.12834	0.0041608	0.36938	0.30452
	TOTAL N AT END	**g**	**1.07**	**1.09**	**1.01**	**1.09**	**0.72**	**1.71**	**0.85**	**0.97**	**1.62**
	Mass N remain in soln	**g**	0.21	0.24	0.23	0.21	0.02	0.13	0.00	0.37	0.30
	Mass in fines + filter	**g**	0.02	0.02	0.00	0.03	0.00	0.09	0.84	0.01	0.01
	Mass N in uptake pellets	**g**	0.81	0.80	0.78	0.83	0.71	1.47	0.00	0.57	1.27
	Mass N lost during sampling	**g**	0.02	0.02	0.00	0.02	0.00	0.02	0.01	0.03	0.03
	Reduction of mass in solution	**g**	0.05	0.07	0.11	0.10	-0.01	0.19	0.45	0.04	0.14
	MASS BALANCE	**g**	**0.06**	**0.09**	**0.17**	**-0.10**	**-0.07**	**-0.04**	**0.03**	**-0.11**	**-0.29**
	RECOVERY (%)		**95**	**93**	**86**	**110**	**110**	**103**	**96**	**113**	**122**

Table B. 22 2010 nitrogen balance 160°C

	Temperature: 160°C		11a	11b	11c	11d	16a	16b	16c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
	START								
	Roasted struvite								
	Conc N as NH3	**mg/L**	3.57	3.57	3.57	0	2.32	2.32	2.32
	Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Wt sample for digesting	**mg**	39.6	39.6	39.6	0	40.5	40.5	40.5
	Wt struvite for uptake	**mg**	19910.7	40334.9	20472.3	0	19990.3	19962.3	39673.8
	Amount of N in roasted struvite	**mg**	448.74	909.06	461.40	0.00	286.28	285.88	568.17
	Amount of N in roasted struvite	**g**	0.45	0.91	0.46	0.00	0.29	0.29	0.57
	Feed								
	Conc N as NH3	**mg/L**	691	698	673	520	875	699	727
	Vol. sample	**L**	0.5	0.5	0.5	0.46	0.564	0.5	0.5
	Amount of N in feed	**mg**	345.5	349	337	239	494	350	364
	Amount of N in feed	**g**	0.3455	0.349	0.34	0.24	0.49	0.35	0.36
	Total N to start	**g**	**0.79**	**1.26**	**0.80**	**0.24**	**0.78**	**0.64**	**0.93**
	Proportion of Mass N in feed		0.435004	0.277411	0.421731	1	0.63287	0.55006	0.39016
	Proportion of N in calcinated pellets		0.564996	0.722589	0.578269	0	0.36713	0.44994	0.60984
	END								
	Uptake: struvite								
	Conc N as NH3	**mg/L**	3.11	2.97	3.27	0	0	2.31	2.06
	Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Wt sample for digesting	**mg**	39.6	40	39.6	0	0	42.3	51.5
	Wt struvite after uptake	**mg**	24809.6	50027.4	25818.7	0	0	24197.8	48258.1
	Amount of N in struvite after uptake	**mg**	487.11	928.63	533.00	0.00	0.00	330.36	482.58
	Amount of N in struvite after uptake	**g**	0.49	0.93	0.53	0.00	0.00	0.33	0.48
	Fines								
	Conc N as NH3	**mg/L**	8.72	12.5	4.77	8.8	3.92	4.97	5.88
	Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Wt sample for digesting	**mg**	40.3	58.5	38.3	40.6	51.2	29.4	32
	Wt fines	**mg**	2315	5275.9	406.5	2206.6	29792.9	88.5	182.3
	Amount of N in fines	**mg**	125.23	281.83	12.66	119.57	570.25	3.74	8.37
	Amount of N in fines	**g**	0.13	0.28	0.01	0.12	0.57	0.00	0.01
	Filter Paper								
	Conc N as NH3	**mg/L**	0	0	0	0	0	0	0
	Vol. sample	**L**	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Amount of N on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Amount of N in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Feed								
0 mins	Conc N as NH3	**mg/L**	675	687	673	0	1270	690	703
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.003375	0.003435	0.003365	0	0.00635	0.00345	0.00352

	Temperature: 160°C		11a	11b	11c	11d	16a	16b	16c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
15 mins	Conc N as NH3	**mg/L**	594	308	627	255	0	630	571
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00297	0.00154	0.003135	0.00128	0	0.00315	0.00286
30 mins	Conc N as NH3	**mg/L**	462	197	600	215	0	613	558
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00231	0.000985	0.003	0.00108	0	0.00307	0.00279
45 mins	Conc N as NH3	**mg/L**	430	154	586	0	0	631	550
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00215	0.00077	0.00293	0	0	0.00316	0.00275
60 mins	Conc N as NH3	**mg/L**	402	122	557	0	0	660	544
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.00201	0.00061	0.002785	0	0	0.0033	0.00272
75 mins	Conc N as NH3	**mg/L**	387	88.5	566	0	0	606	512
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.001935	0.000443	0.00283	0	0	0.00303	0.00256
90 mins	Conc N as NH3	**mg/L**	369	68.9	568	0	0	717	543
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.001845	0.000345	0.00284	0	0	0.00359	0.00272
105 mins	Conc N as NH3	**mg/L**	349	44.1	538	0	0	672	537
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.001745	0.000221	0.00269	0	0	0.00336	0.00269
120 mins	Conc N as NH3	**mg/L**	337	26.2	512	241	8.29	629	537
	Vol. sample	**L**	0.46	0.46	0.46	0.44	0.554	0.46	0.46
	Ammount of N in feed	**g**	0.15502	0.012052	0.23552	0.10604	0.00459	0.28934	0.24702
	TOTAL N AT END	**g**	**0.79**	**1.23**	**0.80**	**0.23**	**0.58**	**0.65**	**0.76**
	Mass N remain in soln (g)		**0.16**	**0.01**	**0.24**	**0.11**	**0.00**	**0.29**	**0.25**
	Mass in fines + filter (g)		**0.13**	**0.28**	**0.01**	**0.12**	**0.57**	**0.00**	**0.01**
	Mass N in uptake pellets (g)		**0.49**	**0.93**	**0.53**	**0.00**	**0.00**	**0.33**	**0.48**
	Mass N lost during sampling (g)		**0.02**	**0.01**	**0.02**	**0.00**	**0.01**	**0.03**	**0.02**
	DIFFERENCE	**g**	**0.01**	**0.03**	**-0.01**	**0.01**	**0.20**	**-0.01**	**0.17**
	Reduction of mass in solution		0.17	0.33	0.08	0.13	0.48	0.03	0.09
	RECOVERY (%)		**99**	**98**	**101**	**95**	**75**	**102**	**82**

Table B. 23 2010 phosphorus balance 80°C

Temperature: 80°C		12a	12b	12c	12d	15a	15b	15c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START								
Roasted struvite								
Conc P as PO4	**mg/L**	24.3	24.3	24.3	24.3	35.5	35.5	35.5
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	40.7	40.7	40.7	40.7	47.3	47.3	47.3
Wt struvite for uptake	**mg**	20159.5	5489	19802.2	40048.3	20068.5	39729.1	19590
Amount of P in roasted struvite	**mg**	3009.07	819.30	2955.73	5977.73	3765.50	7454.46	3675.71
Amount of P in roasted struvite	**g**	3.01	0.82	2.96	5.98	3.77	7.45	3.68
Feed								
Conc P as PO4	**mg/L**	11	0.382	9.43	35.9	9.2	9.38	9.26
Vol. sample	**L**	0.5	0.5	0.5	0.5	0.5	0.5	0.577
Amount of P in feed	**mg**	5.5	0.191	5	18	5	5	5
Amount of P in feed	**g**	0.0055	0.000191	0.00	0.02	0.00	0.00	0.01
Total P to start	**g**	**3.01**	**0.82**	**2.96**	**6.00**	**3.77**	**7.46**	**3.68**
Proportion of Mass P in feed		0.0018245	0.00023307	0.001592664	0.002993825	0.001220128	0.000628758	0.001451
Proportion of P in calcinated pellets		0.9981755	0.99976693	0.998407336	0.997006175	0.998779872	0.999371242	0.998549
END								
Uptake: struvite								
Conc P as PO4	**mg/L**	19.8	35	20.4	23.6	23.5	23.3	0
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	43.9	40.2	42.8	41.8	37.4	38.8	0
Wt struvite after uptake	**mg**	30659.5	7361.8	27926.5	56265.5	24887	49176	0
Amount of P in struvite after uptake	**mg**	3457.05	1602.38	3327.69	7941.78	3909.39	7382.74	0.00
Amount of P in struvite after uptake	**g**	3.46	1.60	3.33	7.94	3.91	7.38	0.00
Fines								
Conc P as PO4	**mg/L**	42.6	0	23.7	26	18.3	18.9	19.4
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	39.8	0	41.6	41.9	36.3	37.4	40.3
Wt fines	**mg**	427.7	23.8	417	918.7	135.2	393.3	30001.5
Amount of P in fines	**mg**	114.45	0.00	59.39	142.52	17.04	49.69	3610.60
Amount of P in fines	**g**	0.11	0.00	0.06	0.14	0.02	0.05	3.61
Filter Paper								
Conc P as PO4	**mg/L**	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Amount of P on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of P in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed								
0 mins Conc P as PO4	**mg/L**	10.3	0	9.15	9.02	9.16	9.26	6390
Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Ammount of P in feed	**g**	0.0000515	0	0.00004575	0.0000451	0.0000458	0.0000463	0.03195

	Temperature: 80°C		12a	12b	12c	12d	15a	15b	15c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
15 mins	Conc P as PO4	**mg/L**	20.5	0	9.93	9.17	2.49	10.2	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.0001025	0	0.00004965	0.00004585	0.00001245	0.000051	0
30 mins	Conc P as PO4	**mg/L**	21.4	0	22.9	53.1	2.2	10.9	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000107	0	0.0001145	0.0002655	0.000011	0.0000545	0
45 mins	Conc P as PO4	**mg/L**	20.9	0	26.2	63.4	2.19	11.2	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.0001045	0	0.000131	0.000317	0.00001095	0.000056	0
60 mins	Conc P as PO4	**mg/L**	22.4	0	57	71.6	2.19	11.2	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000112	0	0.000285	0.000358	0.00001095	0.000056	0
75 mins	Conc P as PO4	**mg/L**	23	0	29.7	75.2	2.24	11.5	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000115	0	0.0001485	0.000376	0.0000112	0.0000575	0
90 mins	Conc P as PO4	**mg/L**	23	0	30.3	78.2	2.35	11.7	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000115	0	0.0001515	0.000391	0.00001175	0.0000585	0
105 mins	Conc P as PO4	**mg/L**	24.3	0	31.6	83.4	2.47	13.6	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.0001215	0	0.000158	0.000417	0.00001235	0.000068	0
120 mins	Conc P as PO4	**mg/L**	61	109	31.7	85.3	2.54	12.1	125
	Vol. sample	**L**	0.46	0.49	0.46	0.46	0.46	0.46	0.567
	Ammount of P in feed	**g**	0.02806	0.05341	0.014582	0.039238	0.0011684	0.005566	0.070875
	TOTAL P AT END	**g**	**3.60**	**1.66**	**3.40**	**8.13**	**3.93**	**7.44**	**3.71**
	Mass P remain in soln (g)		**0.03**	**0.05**	**0.01**	**0.04**	**0.00**	**0.01**	**0.07**
	Mass in fines + filter (g)		**0.11**	**0.00**	**0.06**	**0.14**	**0.02**	**0.05**	**3.61**
	Mass P in uptake pellets (g)		**3.46**	**1.60**	**3.33**	**7.94**	**3.91**	**7.38**	**0.00**
	Mass P lost during sampling (g)		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**
	DIFFERENCE	**g**	**-0.59**	**-0.84**	**-0.44**	**-2.13**	**-0.16**	**0.02**	**-0.03**
	Reduction of mass in solution		-0.02	-0.05	-0.01	-0.02	0.00	0.00	-0.10
	RECOVERY (%)		**119**	**202**	**115**	**136**	**104**	**100**	**101**

Table B. 24 2010 phosphorus balance 105°C

Temperature: 105°C		9a	9b	9c	10a	10b	10c	17a	17b	17c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START										
Roasted struvite										
Conc P as PO4	**mg/L**	32.7	32.7	32.7	36.6	36.6	36.6	29.5	29.5	29.5
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	41.2	41.2	41.2	38.4	38.4	38.4	35.4	35.4	35.4
Wt struvite for uptake	**mg**	20053.8	20026.6	20026	19950	19958	40551	19871	19911.7	39942.4
Amount of P in roasted struvite	**mg**	3979.12	3973.72	3973.61	4753.71	4755.62	9662.54	4139.79	4148.27	8321.33
Amount of P in roasted struvite	**g**	3.98	3.97	3.97	4.75	4.76	9.66	4.14	4.15	8.32
Feed										
Conc P as PO4	**mg/L**	8.68	8.94	8.72	9.74	1.21	9.56	10.1	10.7	10.3
Vol. sample	**L**	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5
Amount of P in feed	**mg**	4.34	4.47	4	5	1	5	6	5	5
Amount of P in feed	**g**	0.00434	0.00447	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Total P to start	**g**	**3.98**	**3.98**	**3.98**	**4.76**	**4.76**	**9.67**	**4.15**	**4.15**	**8.33**
Proportion of Mass P in feed		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Proportion of P in calcinated pellets		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
END										
Uptake: struvite										
Conc P as PO4	**mg/L**	23.7	21.7	23.6	24.1	22.8	23.9	0	29.3	24.1
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	41	39.2	41.2	38.3	39.2	38.2	0	43.6	40.7
Wt struvite after uptake	**mg**	29071.2	30211.9	26399.5	30497.1	30427.8	61526.8	0	24837.8	51166.7
Amount of P in struvite after uptake	**mg**	4201.14	4181.11	3780.51	4797.52	4424.45	9623.63	0.00	4172.86	7574.43
Amount of P in struvite after uptake	**g**	4.20	4.18	3.78	4.80	4.42	9.62	0.00	4.17	7.57
Fines										
Conc P as PO4	**mg/L**	19.5	19.8	19.8	22.1	7.62	20.5	25.4	12.3	19.7
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	38.6	39	37.3	38	11.6	39.1	50.9	23	38.2
Wt fines	**mg**	391.2	516.7	45.8	507	34.5	1525	31605.3	120.4	234.8
Amount of P in fines	**mg**	49.41	65.58	6.08	73.72	5.67	199.89	3942.90	16.10	30.27
Amount of P in fines	**g**	0.05	0.07	0.01	0.07	0.01	0.20	3.94	0.02	0.03
Filter Paper										
Conc P as PO4	**mg/L**	0	0	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05						
Amount of P on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of P in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed										
0 mins Conc P as PO4	**mg/L**	8.68	8.78	38.4	8.97	0	9.21	7300	10.7	10.1

	Temperature: 105°C		9a	9b	9c	10a	10b	10c	17a	17b	17c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	4.34E-05	4.39E-05	0.00019	4.49E-05	0	4.6E-05	0.0365	5.35E-05	5.05E-05
15 mins	Conc P as PO4	**mg/L**	46.9	70.6	0	87.3	0	139	0	3.36	3.6
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000235	0.000353	0	0.000437	0	0.0007	0	1.68E-05	0.000018
30 mins	Conc P as PO4	**mg/L**	48.2	63.1	0	62.1	0	143	0	2.25	3.28
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000241	0.000316	0	0.000311	0	0.00072	0	1.13E-05	1.64E-05
45 mins	Conc P as PO4	**mg/L**	50.9	56.8	0	54	0	158	0	2.1	3.08
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000255	0.000284	0	0.00027	0	0.00079	0	1.05E-05	1.54E-05
60 mins	Conc P as PO4	**mg/L**	54.4	58.1	0	55.7	0	169	0	2.06	3.18
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000272	0.000291	0	0.000279	0	0.00085	0	1.03E-05	1.59E-05
75 mins	Conc P as PO4	**mg/L**	56.2	61.6	0	57.3	0	174	0	2	3.14
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000281	0.000308	0	0.000287	0	0.00087	0	0.00001	1.57E-05
90 mins	Conc P as PO4	**mg/L**	58.6	40.8	0	59.4	0	182	0	4.33	2.99
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000293	0.000204	0	0.000297	0	0.00091	0	2.17E-05	1.5E-05
105 mins	Conc P as PO4	**mg/L**	61.4	68.3	0	59.9	0	189	0	2.25	2.97
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000307	0.000342	0	0.0003	0	0.00095	0	1.13E-05	1.49E-05
120 mins	Conc P as PO4	**mg/L**	66.5	69.4	882.5	62	178	198	196	2.23	3.12
	Vol. sample	**L**	0.46	0.46	0.46	0.46	0.49	0.46	0.56	0.46	0.46
	Ammount of P in feed	**g**	0.03059	0.031924	0.40595	0.02852	0.08722	0.09108	0.10976	0.001026	0.001435
	TOTAL P AT END	**g**	**4.28**	**4.28**	**4.19**	**4.90**	**4.52**	**9.92**	**4.09**	**4.19**	**7.61**
	Mass P remain in soln	**g**	0.03	0.03	0.41	0.03	0.09	0.09	0.11	0.00	0.00
	Mass in fines + filter	**g**	0.05	0.07	0.01	0.07	0.01	0.20	3.94	0.02	0.03
	Mass P in uptake pellets	**g**	4.20	4.18	3.78	4.80	4.42	9.62	0.00	4.17	7.57
	Mass P lost during sampling	**g**	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.00
	Reduction of mass in solution	**g**	-0.03	-0.03	-0.40	-0.03	-0.09	-0.09	-0.14	0.00	0.00
	MASS BALANCE	**g**	**-0.30**	**-0.30**	**-0.21**	**-0.14**	**0.24**	**-0.25**	**0.06**	**-0.04**	**0.72**
	RECOVERY (%)		**108**	**108**	**105**	**103**	**95**	**103**	**99**	**101**	**91**

Table B. 25 2010 phosphorus balance 160°C

	Temperature: 160°C		11a	11b	11c	11d	16a	16b	16c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
	START								
	Roasted struvite								
	Conc P as PO4	**mg/L**	28.5	28.5	28.5	0	31.5	31.5	31.5
	Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Wt sample for digesting	**mg**	39.6	39.6	39.6	0	40.5	40.5	40.5
	Wt struvite for uptake	**mg**	19910.7	40334.9	20472.3	0	19990.3	19962.3	39673.8
	Amount of P in roasted struvite	**mg**	3582.42	7257.23	3683.46	0.00	3887.00	3881.56	7714.35
	Amount of P in roasted struvite	**g**	3.58	7.26	3.68	0.00	3.89	3.88	7.71
	Feed								
	Conc P as PO4	**mg/L**	8.88	12.2	11.4	686	10.4	10.1	9.99
	Vol. sample	**L**	0.5	0.5	0.5	0.46	0.564	0.5	0.5
	Amount of P in feed	**mg**	4.44	6.1	6	316	6	5	5
	Amount of P in feed	**g**	0.00444	0.0061	0.01	0.32	0.01	0.01	0.00
	Total P to start	**g**	**3.59**	**7.26**	**3.69**	**0.32**	**3.89**	**3.89**	**7.72**
	Proportion of Mass P in feed		0.001238	0.0008398	0.0015451	1	0.001507	0.0013	0.00064708
	Proportion of P in calcinated pellets		0.998762	0.9991602	0.9984549	0	0.998493	0.9987	0.99935292
	END								
	Uptake: struvite								
	Conc P as PO4	**mg/L**	21.2	21.6	14.5	0	0	26.6	20.6
	Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Wt sample for digesting	**mg**	39.6	40	39.6	0	0	42.3	51.5
	Wt struvite after uptake	**mg**	24809.6	50027.4	25818.7	0	0	24197.8	48258.1
	Amount of P in struvite after uptake	**mg**	3320.48	6753.70	2363.45	0.00	0.00	3804.15	4825.81
	Amount of P in struvite after uptake	**g**	3.32	6.75	2.36	0.00	0.00	3.80	4.83
	Fines								
	Conc P as PO4	**mg/L**	20.4	30.4	3.36	20.7	21.8	14.8	16.7
	Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Wt sample for digesting	**mg**	40.3	58.5	38.3	40.6	51.2	29.4	32
	Wt fines	**mg**	2315	5275.9	406.5	2206.6	29792.9	88.5	182.3
	Amount of P in fines	**mg**	292.97	685.42	8.92	281.26	3171.31	11.14	23.78
	Amount of P in fines	**g**	0.29	0.69	0.01	0.28	3.17	0.01	0.02
	Filter Paper								
	Conc P as PO4	**mg/L**	0	0	0	0	0	0	0
	Vol. sample	**L**	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Amount of P on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Amount of P in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Feed								
0 mins	Conc P as PO4	**mg/L**	9.55	10.8	11.4	0	5910	10.1	10.2
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	4.78E-05	0.000054	0.000057	0	0.02955	5.1E-05	0.000051

	Temperature: 160°C		11a	11b	11c	11d	16a	16b	16c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
15 mins	Conc P as PO4	**mg/L**	236	165	523	22.4	0	14.4	17.3
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.00118	0.000825	0.002615	0.000112	0	7.2E-05	0.0000865
30 mins	Conc P as PO4	**mg/L**	93.2	146	571	16.5	0	8.94	12.7
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000466	0.00073	0.002855	8.25E-05	0	4.5E-05	0.0000635
45 mins	Conc P as PO4	**mg/L**	94.3	150	583	0	0	7	10.7
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000472	0.00075	0.002915	0	0	3.5E-05	0.0000535
60 mins	Conc P as PO4	**mg/L**	92.5	150	599	0	0	6.23	9.67
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000463	0.00075	0.002995	0	0	3.1E-05	0.00004835
75 mins	Conc P as PO4	**mg/L**	90.1	149	621	0	0	5.61	8.87
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000451	0.000745	0.003105	0	0	2.8E-05	0.00004435
90 mins	Conc P as PO4	**mg/L**	87.4	156	622	0	0	5.29	8.11
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000437	0.00078	0.00311	0	0	2.6E-05	0.00004055
105 mins	Conc P as PO4	**mg/L**	83.8	178	630	0	0	5.28	7.99
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of P in feed	**g**	0.000419	0.00089	0.00315	0	0	2.6E-05	0.00003995
120 mins	Conc P as PO4	**mg/L**	82.8	190	646	15.6	155	5.15	7.46
	Vol. sample	**L**	0.46	0.46	0.46	0.44	0.554	0.46	0.46
	Ammount of P in feed	**g**	0.038088	0.0874	0.29716	0.006864	0.08587	0.00237	0.0034316
	TOTAL P AT END	**g**	**3.66**	**7.53**	**2.69**	**0.29**	**3.29**	**3.82**	**4.85**
	Mass P remain in soln (g)		**0.04**	**0.09**	**0.30**	**0.01**	**0.09**	**0.00**	**0.00**
	Mass in fines + filter (g)		**0.29**	**0.69**	**0.01**	**0.28**	**3.17**	**0.01**	**0.02**
	Mass P in uptake pellets (g)		**3.32**	**6.75**	**2.36**	**0.00**	**0.00**	**3.80**	**4.83**
	Mass P lost during sampling (g)		**0.00**	**0.01**	**0.02**	**0.00**	**0.03**	**0.00**	**0.00**
	DIFFERENCE	**g**	**-0.07**	**-0.27**	**1.00**	**0.03**	**0.61**	**0.07**	**2.87**
	Reduction of mass in solution		-0.04	-0.09	-0.31	0.31	-0.11	0.00	0.00
	RECOVERY (%)		**102**	**104**	**73**	**91**	**84**	**98**	**63**

Table B. 26 2010 magnesium balance 80°C

Temperature: 80°C		12a	12b	12c	12d	15a	15b	15c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START								
Roasted struvite								
Conc N as NH3	**mg/L**	18.92	18.92	18.92	18.92	27.284	27.284	27.284
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	40.7	40.7	40.7	40.7	47.3	47.3	47.3
Wt struvite for uptake	**mg**	20159.5	5489	19802.2	40048.3	20068.5	39729.1	19590
Amount of N in roasted struvite	**mg**	2342.86	637.91	2301.34	4654.26	2894.02	5729.22	2825.02
Amount of N in roasted struvite	**g**	2.34	0.64	2.30	4.65	2.89	5.73	2.83
Feed								
Conc N as NH3	**mg/L**	34.47	1.2825	31.1425	31.3875	30.6175	31.29	31.1375
Vol. sample	**L**	0.5	0.5	0.5	0.5	0.5	0.5	0.577
Amount of N in feed	**mg**	17.235	0.64125	16	16	15	16	18
Amount of N in feed	**g**	0.017235	0.00064125	0.02	0.02	0.02	0.02	0.02
Total N to start	**g**	**2.36**	**0.64**	**2.32**	**4.67**	**2.91**	**5.74**	**2.84**
Proportion of Mass N in feed		0.0073027	0.001004225	0.006720703	0.003360578	0.005261949	0.002723301	0.00632
Proportion of N in calcinated pellets		0.9926973	0.998995775	0.993279297	0.996639422	0.994738051	0.997276699	0.99368
END								
Uptake: struvite								
Conc N as NH3	**mg/L**	15.889	26.106	16.642	16.227	17.5175	18.1975	0
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	43.9	40.2	42.8	41.8	37.4	38.8	0
Wt struvite after uptake	**mg**	30659.5	7361.8	27926.5	56265.5	24887	49176	0
Amount of N in struvite after uptake	**mg**	2774.20	1195.19	2714.68	5460.65	2914.16	5765.98	0.00
Amount of N in struvite after uptake	**g**	2.77	1.20	2.71	5.46	2.91	5.77	0.00
Fines								
Conc N as NH3	**mg/L**	15.725556	0	18.04	19.893	13.899	14.684	14.8815
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	39.8	0	41.6	41.9	36.3	37.4	40.3
Wt fines	**mg**	427.7	23.8	417	918.7	135.2	393.3	30001.5
Amount of N in fines	**mg**	42.25	0.00	45.21	109.04	12.94	38.60	2769.65
Amount of N in fines	**g**	0.04	0.00	0.05	0.11	0.01	0.04	2.77
Filter Paper								
Conc N as NH3	**mg/L**	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Amount of N on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of N in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed								
0 mins Conc N as NH3	**mg/L**	34.835	0	31.4475	31.205	30.8	31.045	5267.75
Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Ammount of N in feed	**g**	0.0001742	0	0.000157238	0.000156025	0.000154	0.000155225	0.026339

	Temperature: 80°C		12a	12b	12c	12d	15a	15b	15c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
15 mins	Conc N as NH3	**mg/L**	25.215	0	16	8.4275	14.3625	3.3	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0001261	0	0.00008	4.21375E-05	7.18125E-05	0.0000165	0
30 mins	Conc N as NH3	**mg/L**	22.9025	0	14.29	8.1225	13.8125	3.1775	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0001145	0	0.00007145	4.06125E-05	6.90625E-05	1.58875E-05	0
45 mins	Conc N as NH3	**mg/L**	21.8075	0	12.885	7.695	13.5675	3.1775	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.000109	0	0.000064425	0.000038475	6.78375E-05	1.58875E-05	0
60 mins	Conc N as NH3	**mg/L**	21.8075	0	11.8475	6.9625	13.5675	2.995	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.000109	0	5.92375E-05	3.48125E-05	6.78375E-05	0.000014975	0
75 mins	Conc N as NH3	**mg/L**	21.1975	0	11.175	6.84	14.055	3.1175	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.000106	0	0.000055875	0.0000342	0.000070275	1.55875E-05	0
90 mins	Conc N as NH3	**mg/L**	22.905	0	10.625	6.4725	14.3	3.055	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0001145	0	0.000053125	3.23625E-05	0.0000715	0.000015275	0
105 mins	Conc N as NH3	**mg/L**	21.3125	0	10.015	6.4775	14.055	4.725	0
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0001066	0	0.000050075	3.23875E-05	0.000070275	0.000023625	0
120 mins	Conc N as NH3	**mg/L**	51.1925	46.2875	9.5275	5.745	14.1775	3.3925	50.0375
	Vol. sample	**L**	0.46	0.49	0.46	0.46	0.46	0.46	0.567
	Ammount of N in feed	**g**	0.0235486	0.022680875	0.00438265	0.0026427	0.00652165	0.00156055	0.028371
	TOTAL N AT END	**g**	**2.84**	**1.22**	**2.76**	**5.57**	**2.93**	**5.81**	**2.82**
	Mass N remain in soln (g)		**0.02**	**0.02**	**0.00**	**0.00**	**0.01**	**0.00**	**0.03**
	Mass in fines + filter (g)		**0.04**	**0.00**	**0.05**	**0.11**	**0.01**	**0.04**	**2.77**
	Mass N in uptake pellets (g)		**2.77**	**1.20**	**2.71**	**5.46**	**2.91**	**5.77**	**0.00**
	Mass N lost during sampling (g)		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**
	DIFFERENCE	**g**	**-0.48**	**-0.58**	**-0.45**	**-0.90**	**-0.02**	**-0.06**	**0.02**
	Reduction of mass in solution		-0.01	-0.02	0.01	0.01	0.01	0.01	-0.04
	RECOVERY (%)		**120**	**191**	**119**	**119**	**101**	**101**	**99**

Table B. 27 2010 magnesium balance 105°C

Temperature: 105°C		9a	9b	9c	10a	10b	10c	17a	17b	17c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START										
Roasted struvite										
Conc N as NH3	**mg/L**	27.2885	27.2885	27.2885	25.666	25.666	25.666	23.0418	23.04175	23.0418
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	41.2	41.2	41.2	38.4	38.4	38.4	35.4	35.4	35.4
Wt struvite for uptake	**mg**	20053.8	20026.6	20026	19950	19958	40551	19871	19911.7	39942.4
Amount of N in roasted struvite	**mg**	3320.62	3316.12	3316.02	3333.57	3334.91	6775.92	3233.49	3240.12	6499.60
Amount of N in roasted struvite	**g**	3.32	3.32	3.32	3.33	3.33	6.78	3.23	3.24	6.50
Feed										
Conc N as NH3	**mg/L**	31.29	31.29	32.8525	30.7775	0	30.8375	30.386	32.00723	31.191
Vol. sample	**L**	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5
Amount of N in feed	**mg**	15.645	15.645	16	15	0	15	18	16	16
Amount of N in feed	**g**	0.015645	0.015645	0.02	0.02	0.00	0.02	0.02	0.02	0.02
Total N to start	**g**	**3.34**	**3.33**	**3.33**	**3.35**	**3.33**	**6.79**	**3.25**	**3.26**	**6.52**
Proportion of Mass N in feed		0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Proportion of N in calcinated pellets		1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
END										
Uptake: struvite										
Conc N as NH3	**mg/L**	17.9267	16.5768	18.481649	17.17629	17.433299	16.76299	0	37.74607	19.2385
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	41	39.2	41.2	38.3	39.2	38.2	0	43.6	40.7
Wt struvite after uptake	**mg**	29071.2	30211.9	26399.5	30497.1	30427.8	61526.8	0	24837.8	51166.7
Amount of N in struvite after uptake	**mg**	3177.75	3193.98	2960.60	3419.24	3383.02	6749.82	0.00	5375.74	6046.49
Amount of N in struvite after uptake	**g**	3.18	3.19	2.96	3.42	3.38	6.75	0.00	5.38	6.05
Fines										
Conc N as NH3	**mg/L**	14.4161	14.7172	15.397113	14.82763	5.2668041	15.10485	19.0779	9.76896	14.743
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	38.6	39	37.3	38	11.6	39.1	50.9	23	38.2
Wt fines	**mg**	391.2	516.7	45.8	507	34.5	1525	31605.3	120.4	234.8
Amount of N in fines	**mg**	36.53	48.75	4.73	49.46	3.92	147.28	2961.50	12.78	22.65
Amount of N in fines	**g**	0.04	0.05	0.00	0.05	0.00	0.15	2.96	0.01	0.02
Filter Paper										
Conc N as NH3	**mg/L**	0	0	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05						
Amount of N on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of N in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed										
0 mins Conc N as NH3	**mg/L**	30.6775	30.0675	43.6	30.41	0	30.655	1428.25	31.23025	32.0592

	Temperature: 105°C		9a	9b	9c	10a	10b	10c	17a	17b	17c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.000153	0.0001503	0.000218	0.000152	0	0.000153	0.00714	0.000156	0.00016
15 mins	Conc N as NH3	**mg/L**	18.5775	39.905	0	57.4	0	26.135	0	17.77938	13.6194
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	9.29E-05	0.0001995	0	0.000287	0	0.000131	0	8.89E-05	6.8E-05
30 mins	Conc N as NH3	**mg/L**	15.155	30.6775	0	35.1725	0	16.1225	0	16.71673	12.6474
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	7.58E-05	0.0001534	0	0.000176	0	8.06E-05	0	8.36E-05	6.3E-05
45 mins	Conc N as NH3	**mg/L**	13.69	22.9775	0	25.8925	0	15.51	0	16.48353	12.4661
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	6.85E-05	0.0001149	0	0.000129	0	7.76E-05	0	8.24E-05	6.2E-05
60 mins	Conc N as NH3	**mg/L**	12.7125	19.0675	0	25.16	0	17.045	0	16.53494	12.3108
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	6.36E-05	9.534E-05	0	0.000126	0	8.52E-05	0	8.27E-05	6.2E-05
75 mins	Conc N as NH3	**mg/L**	11.49	18.2125	0	22.5325	0	14.7075	0	15.83534	12.57
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	5.75E-05	9.106E-05	0	0.000113	0	7.35E-05	0	7.92E-05	6.3E-05
90 mins	Conc N as NH3	**mg/L**	9.7775	16.3775	0	21.3725	0	14.7075	0	17.98661	12.4921
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	4.89E-05	8.189E-05	0	0.000107	0	7.35E-05	0	8.99E-05	6.2E-05
105 mins	Conc N as NH3	**mg/L**	10.145	15.8275	0	20.2725	0	14.4625	0	16.71673	12.1291
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	5.07E-05	7.914E-05	0	0.000101	0	7.23E-05	0	8.36E-05	6.1E-05
120 mins	Conc N as NH3	**mg/L**	9.045	15.645	595.7	19.0525	78.53	14.7075	3.595	16.56091	11.9218
	Vol. sample	**L**	0.46	0.46	0.46	0.46	0.49	0.46	0.56	0.46	0.46
	Ammount of N in feed	**g**	0.004161	0.0071967	0.274022	0.008764	0.0384797	0.006765	0.00201	0.007618	0.00548
	TOTAL N AT END	**g**	**3.22**	**3.25**	**3.24**	**3.48**	**3.43**	**6.90**	**2.97**	**5.40**	**6.08**
	Mass N remain in soln	**g**	0.00	0.01	0.27	0.01	0.04	0.01	0.00	0.01	0.01
	Mass in fines + filter	**g**	0.04	0.05	0.00	0.05	0.00	0.15	2.96	0.01	0.02
	Mass N in uptake pellets	**g**	3.18	3.19	2.96	3.42	3.38	6.75	0.00	5.38	6.05
	Mass N lost during sampling	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
	Reduction of mass in solution	**g**	0.01	0.01	-0.26	0.01	-0.04	0.01	0.01	0.01	0.01
	MASS BALANCE	**g**	**0.12**	**0.08**	**0.09**	**-0.13**	**-0.09**	**-0.11**	**0.28**	**-2.14**	**0.44**
	RECOVERY (%)		**96**	**98**	**97**	**104**	**103**	**102**	**91**	**166**	**93**

Table B. 28 2010 magnesium balance 160°C

Temperature: 160°C		11a	11b	11c	11d	16a	16b	16c
Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
START								
Roasted struvite								
Conc N as NH3	**mg/L**	26.253	26.253	26.253	0	24.80612	24.80612	24.80612
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	39.6	39.6	39.6	0	40.5	40.5	40.5
Wt struvite for uptake	**mg**	19910.7	40334.9	20472.3	0	19990.3	19962.3	39673.8
Amount of N in roasted struvite	**mg**	3299.97	6685.05	3393.05	0.00	3061.00	3056.71	6075.02
Amount of N in roasted struvite	**g**	3.30	6.69	3.39	0.00	3.06	3.06	6.08
Feed								
Conc N as NH3	**mg/L**	30.215	33.025	33.33	528.48	31.5815	30.824	30.5795
Vol. sample	**L**	0.5	0.5	0.5	0.46	0.564	0.5	0.5
Amount of N in feed	**mg**	15.1075	16.5125	17	243	18	15	15
Amount of N in feed	**g**	0.0151075	0.0165125	0.02	0.24	0.02	0.02	0.02
Total N to start	**g**	**3.32**	**6.70**	**3.41**	**0.24**	**3.08**	**3.07**	**6.09**
Proportion of Mass N in feed		0.0045572	0.00246398	0.0048875	1	0.00578534	0.00501673	0.0025105
Proportion of N in calcinated pellets		0.9954428	0.99753602	0.9951125	0	0.99421466	0.99498327	0.9974895
END								
Uptake: struvite								
Conc N as NH3	**mg/L**	19.453	19.868	16.4588889	0	0	21.32826	17.36439
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	39.6	40	39.6	0	0	42.3	51.5
Wt struvite after uptake	**mg**	24809.6	50027.4	25818.7	0	0	24197.8	48258.1
Amount of N in struvite after uptake	**mg**	3046.85	6212.15	2682.75	0.00	0.00	3050.22	4067.83
Amount of N in struvite after uptake	**g**	3.05	6.21	2.68	0.00	0.00	3.05	4.07
Fines								
Conc N as NH3	**mg/L**	15.787	22.434	0.21777778	19.5011111	17.92672	10.971	13.29823
Vol. sample	**L**	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wt sample for digesting	**mg**	40.3	58.5	38.3	40.6	51.2	29.4	32
Wt fines	**mg**	2315	5275.9	406.5	2206.6	29792.9	88.5	182.3
Amount of N in fines	**mg**	226.72	505.81	0.58	264.97	2607.86	8.26	18.94
Amount of N in fines	**g**	0.23	0.51	0.00	0.26	2.61	0.01	0.02
Filter Paper								
Conc N as NH3	**mg/L**	0	0	0	0	0	0	0
Vol. sample	**L**	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Amount of N on filter paper	**mg**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Amount of N in filter paper	**g**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feed								
0 mins Conc N as NH3	**mg/L**	31.3225	31.19	33.33	0	3605.5	30.9215	30.5795
Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Ammount of N in feed	**g**	0.0001566	0.00015595	0.00016665	0	0.0180275	0.00015461	0.0001529

	Temperature: 160°C		11a	11b	11c	11d	16a	16b	16c
	Sample	**Unit**	**pH 8**	**pH 8**	**pH 8**	**pH 8**	**pH 9**	**pH 9**	**pH 9**
15 mins	Conc N as NH3	**mg/L**	183.445	105.065	436.7675	12.9175	0	39.5015	43.8035
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0009172	0.00052533	0.00218384	6.4588E-05	0	0.00019751	0.00021902
30 mins	Conc N as NH3	**mg/L**	80.43	106.2875	485.445	8.1675	0	35.5905	40.5035
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0004022	0.00053144	0.00242723	4.0838E-05	0	0.00017795	0.00020252
45 mins	Conc N as NH3	**mg/L**	86.83	103.72	496.575	0	0	33.977	39.4525
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0004342	0.0005186	0.00248288	0	0	0.00016989	0.00019726
60 mins	Conc N as NH3	**mg/L**	87.02	96.015	493.64	0	0	33.6595	37.9615
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0004351	0.00048008	0.0024682	0	0	0.0001683	0.00018981
75 mins	Conc N as NH3	**mg/L**	82.9875	87.575	491.9275	0	0	35	37.7415
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0004149	0.00043788	0.00245964	0	0	0.000175	0.00018871
90 mins	Conc N as NH3	**mg/L**	77.61	89.9	485.69	0	0	125.46	37.096
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0003881	0.0004495	0.00242845	0	0	0.0006273	0.00018548
105 mins	Conc N as NH3	**mg/L**	73.0275	98.8275	494.375	0	0	32.2905	36.6165
	Vol. sample	**L**	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Ammount of N in feed	**g**	0.0003651	0.00049414	0.00247188	0	0	0.00016145	0.00018308
120 mins	Conc N as NH3	**mg/L**	71.6225	103.5975	496.085	8.9	136.8325	32.486	35.9935
	Vol. sample	**L**	0.46	0.46	0.46	0.44	0.554	0.46	0.46
	Ammount of N in feed	**g**	0.0329464	0.04765485	0.2281991	0.003916	0.07580521	0.01494356	0.01655701
	TOTAL N AT END	**g**	**3.31**	**6.77**	**2.93**	**0.27**	**2.70**	**3.08**	**4.10**
	Mass N remain in soln (g)		**0.03**	**0.05**	**0.23**	**0.00**	**0.08**	**0.01**	**0.02**
	Mass in fines + filter (g)		**0.23**	**0.51**	**0.00**	**0.26**	**2.61**	**0.01**	**0.02**
	Mass N in uptake pellets (g)		**3.05**	**6.21**	**2.68**	**0.00**	**0.00**	**3.05**	**4.07**
	Mass N lost during sampling (g)		**0.00**	**0.00**	**0.02**	**0.00**	**0.02**	**0.00**	**0.00**
	DIFFERENCE	**g**	**0.01**	**-0.07**	**0.48**	**-0.03**	**0.38**	**0.00**	**1.99**
	Reduction of mass in solution		-0.02	-0.03	-0.23	0.24	-0.08	0.00	0.00
	RECOVERY (%)		**100**	**101**	**86**	**111**	**88**	**100**	**67**

Appendix C: Elemental analysis spreadsheet

Table C. 1 Elemental analysis solver

user input %N	=	0.053	
user input %H	=	0.064	
%N + %H (from input)	=	0.117	
Mass of MgHPO4	=	120.286	
Solve%N Equation (Eqn 14)	=	0.053	<=go to target cell
Solve %H Equation (Eqn 15)	=	0.064	<=go to target cell
%N + %H (output)	=	0.117	<= Target cell soln
Input = output= ?	=	YES	
X solved (amount N)	=	0.902	
Y solved (amount H2O)	=	5.705	

Appendix D: Mass balance graphs

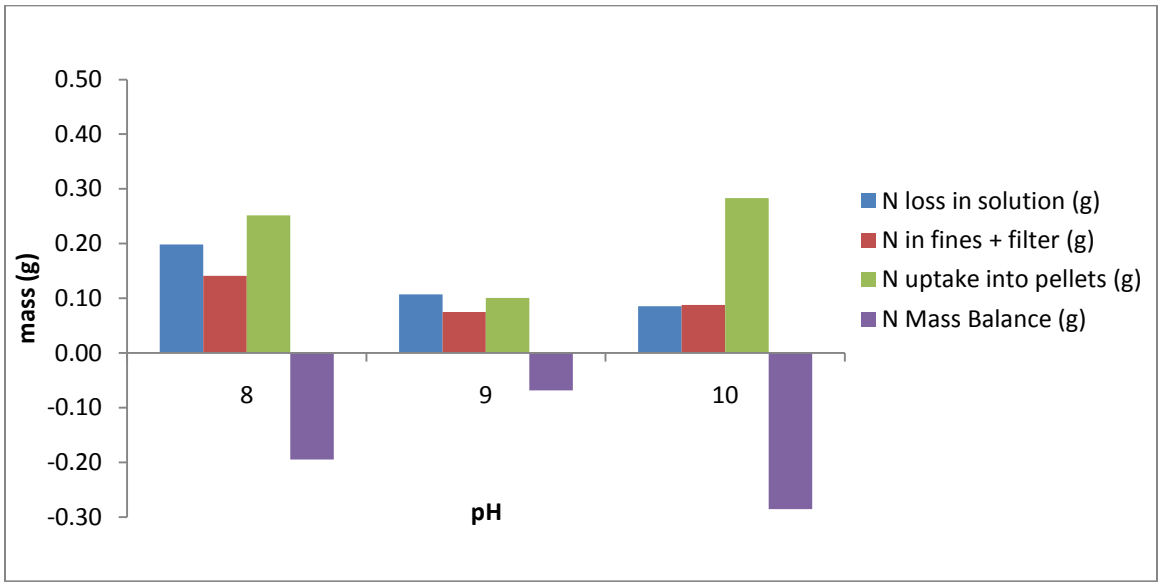

Figure D. 1 2009 nitrogen mass balance @ T=100 for pH 8,9,10

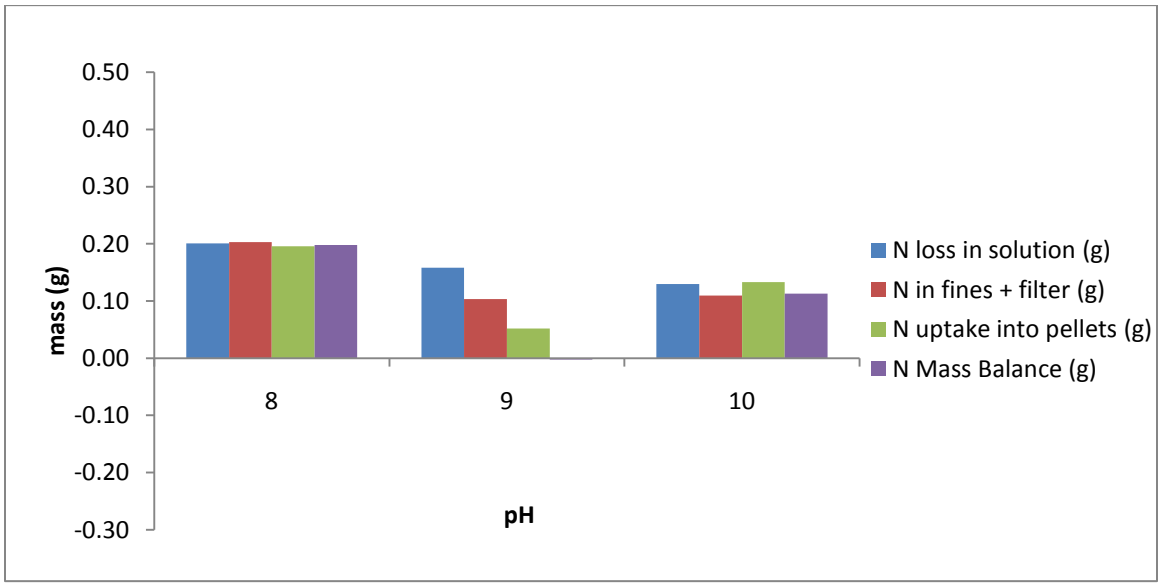

Figure D. 2 2009 nitrogen mass balance @ T=120 for pH 8,9,10

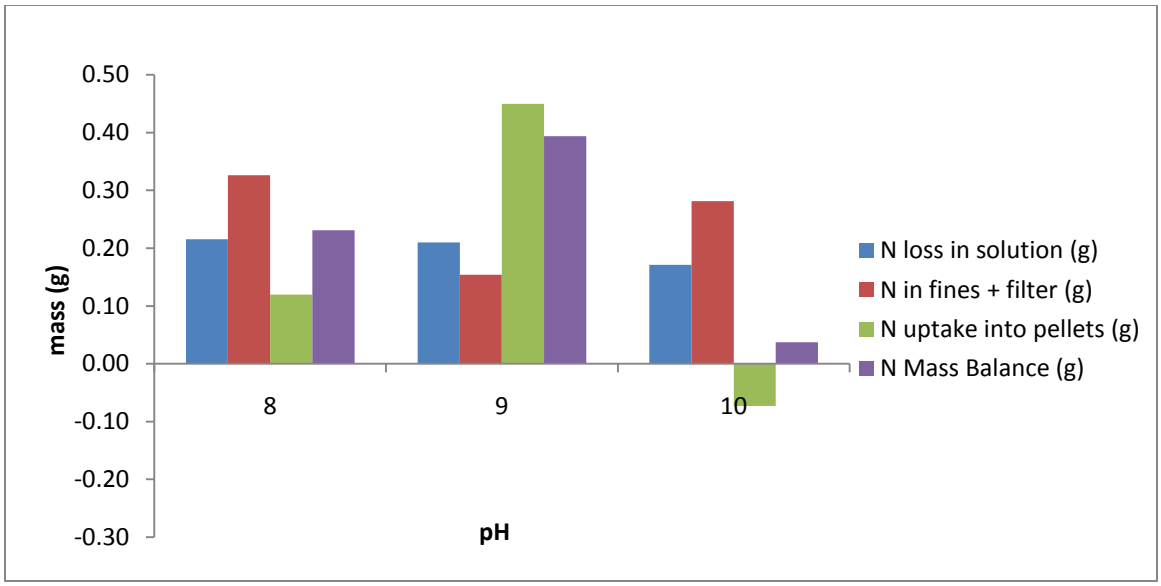

Figure D. 3 2009 nitrogen mass balance @ T=140 for pH 8,9,10

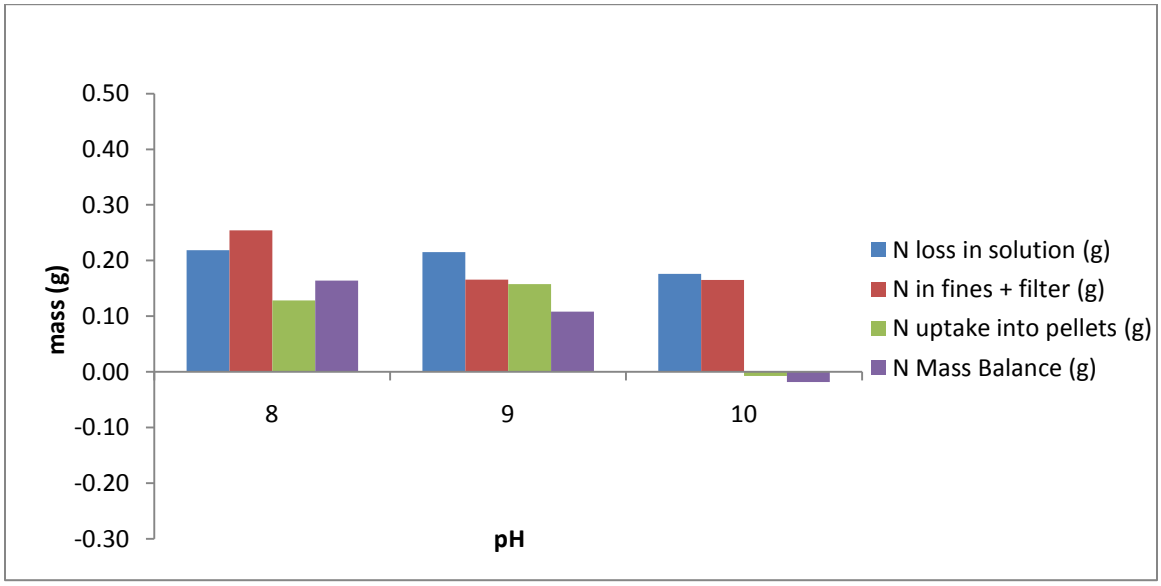

Figure D. 4 2009 nitrogen mass balance @ T=160 for pH 8,9,10

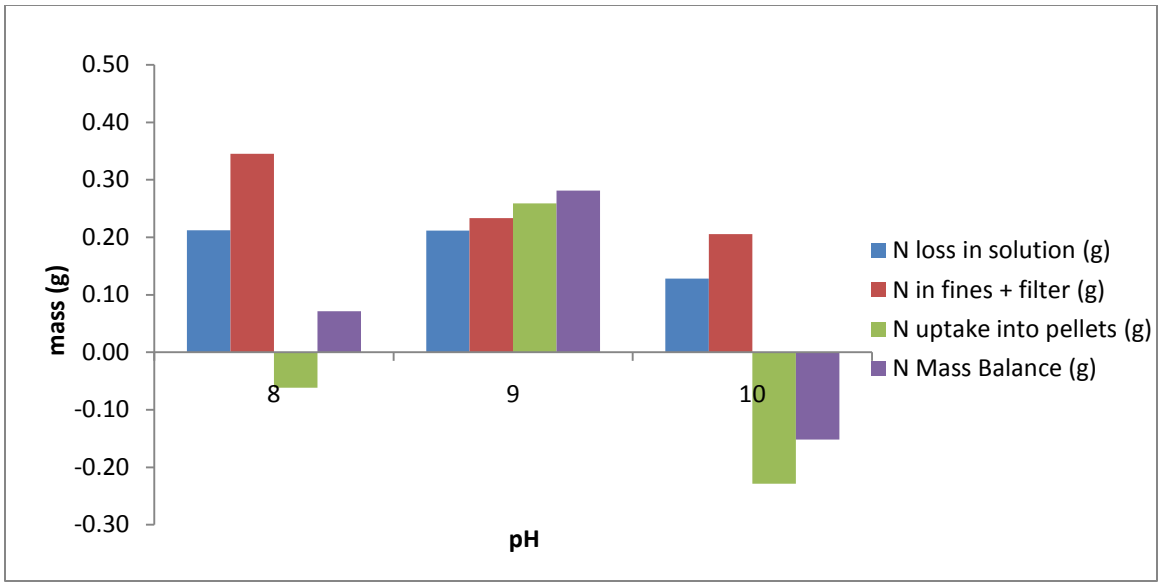

Figure D. 5 2009 nitrogen mass balance @ T=180 for pH 8,9,10

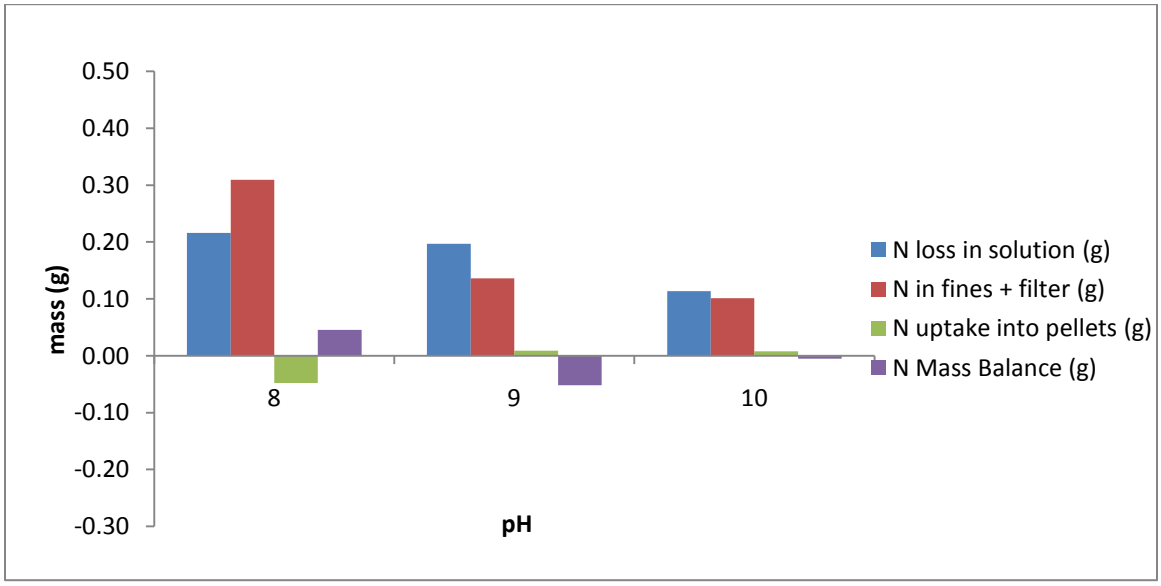

Figure D. 6 2009 nitrogen mass balance @ T=200 for pH 8,9,10

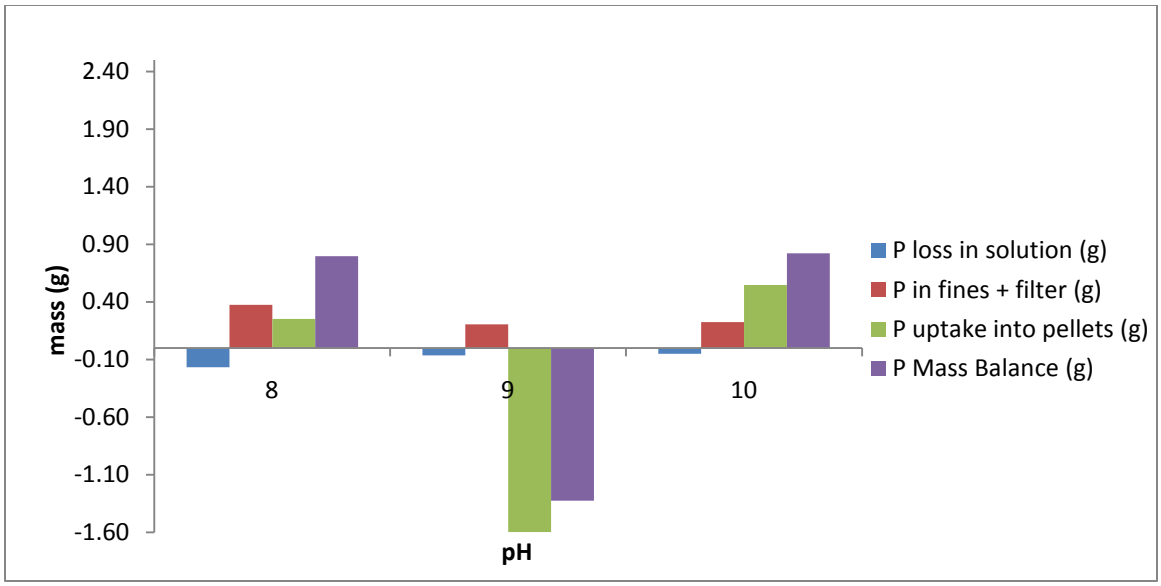

Figure D. 7 2009 phosphorus mass balance @ T=100 for pH 8,9,10

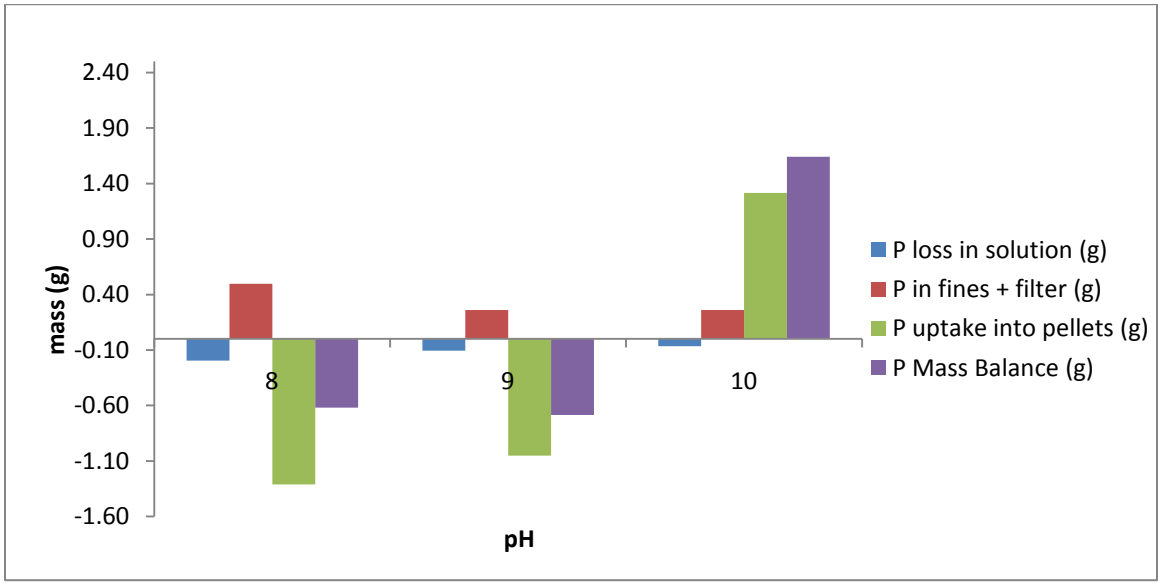

Figure D. 8 2009 phosphorus mass balance @ T=120 for pH 8,9,10

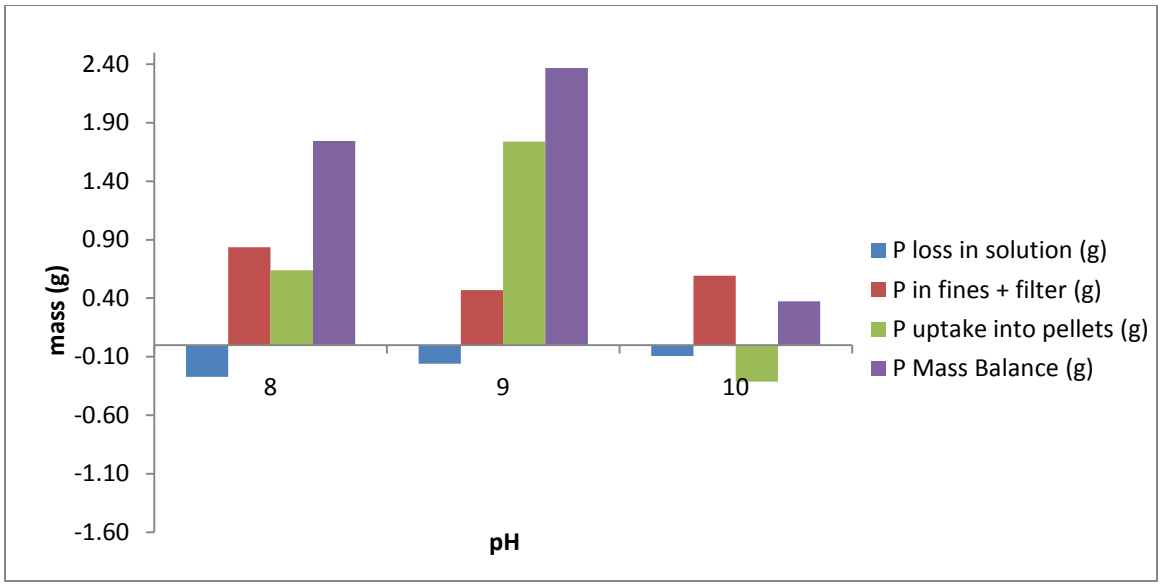

Figure D. 9 2009 phosphorus mass balance @ T=140 for pH 8,9,10

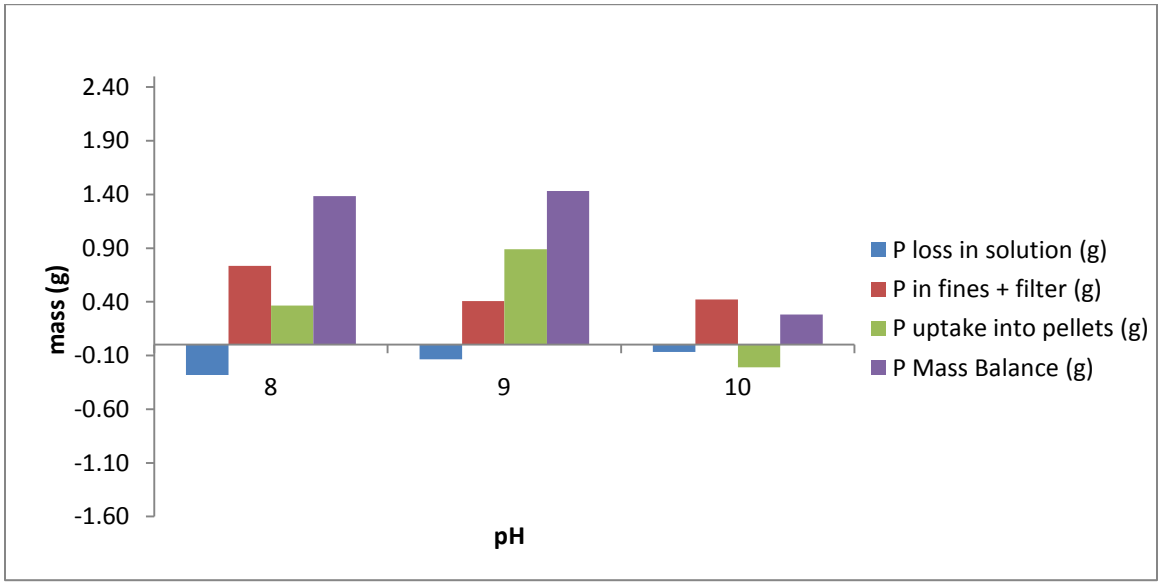

Figure D. 10 2009 phosphorus mass balance @ T=160 for pH 8,9,10

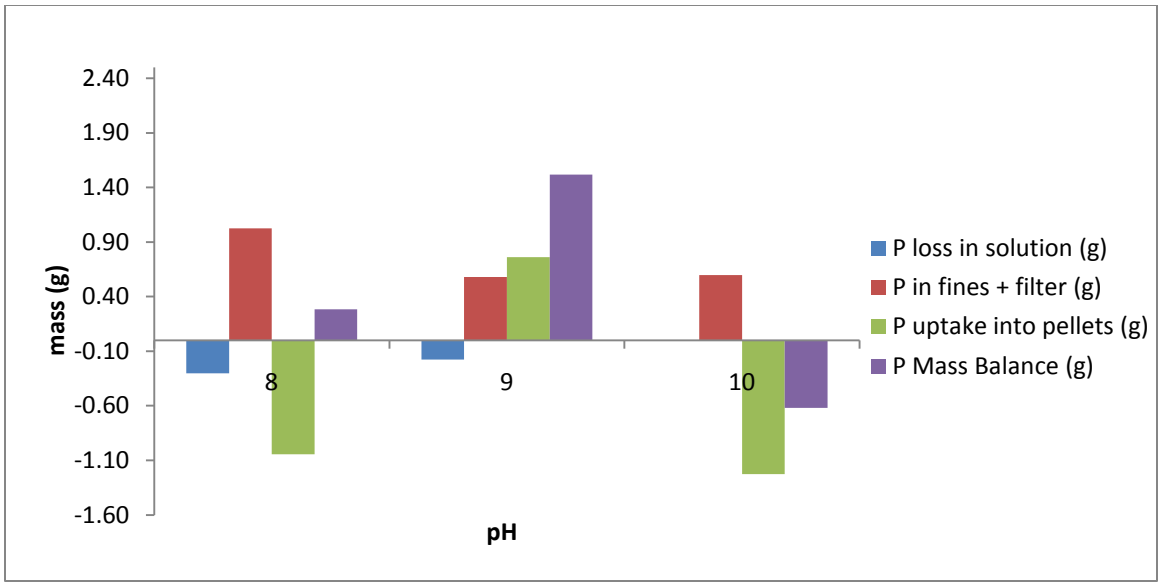

Figure D. 11 2009 phosphorus mass balance @ T=180 for pH 8,9,10

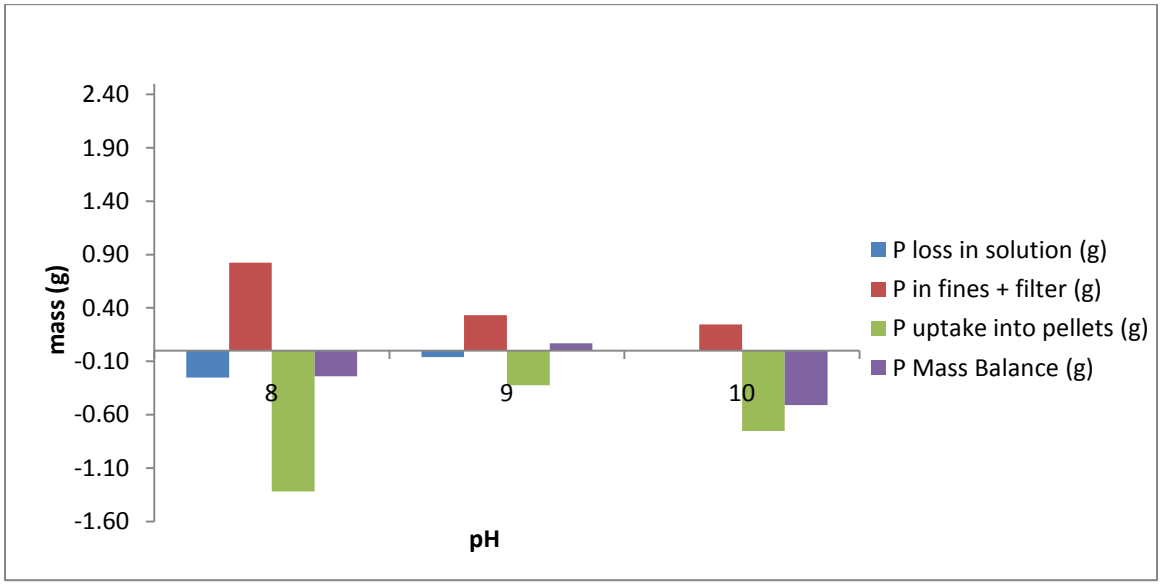

Figure D. 12 2009 phosphorus mass balance @ T=200 for pH 8,9,10

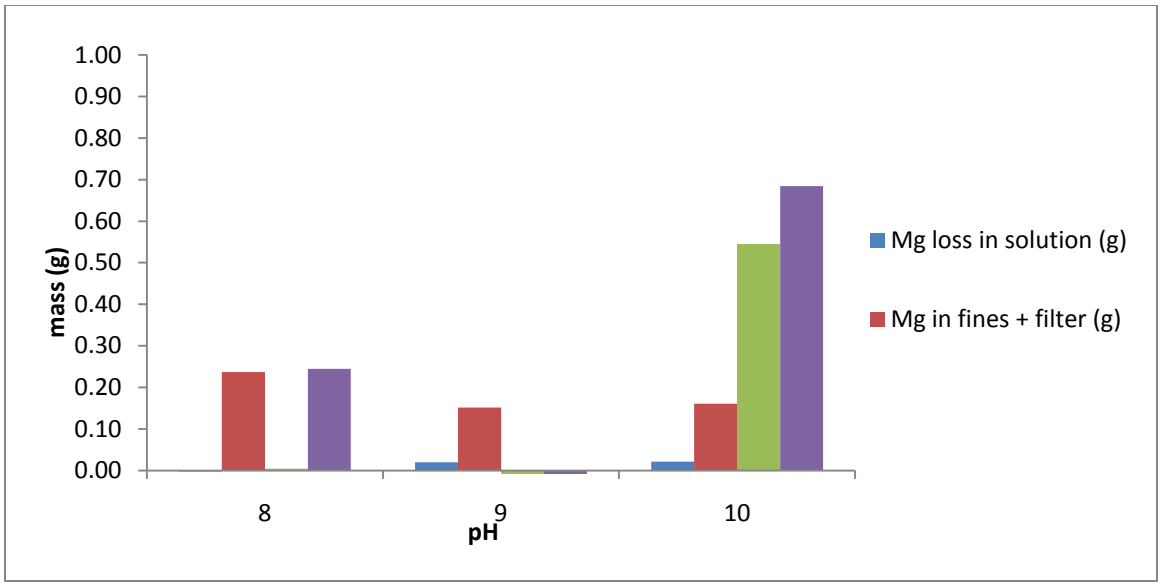

Figure D. 13 2009 magnesium mass balance @ T=100 for pH 8,9,10

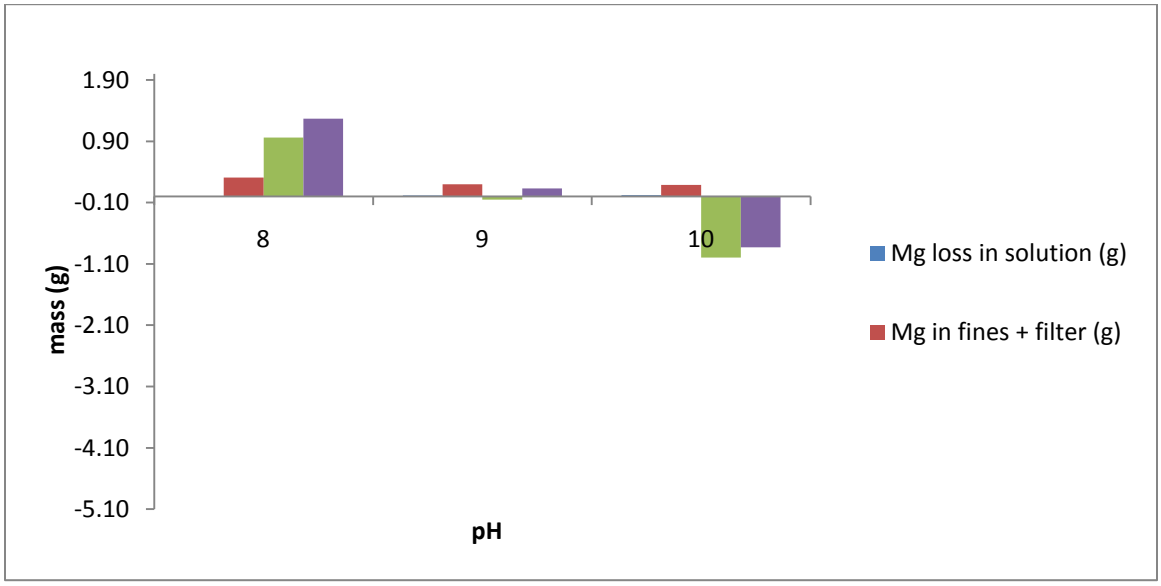

Figure D. 14 2009 magnesium mass balance @ T=120 for pH 8,9,10

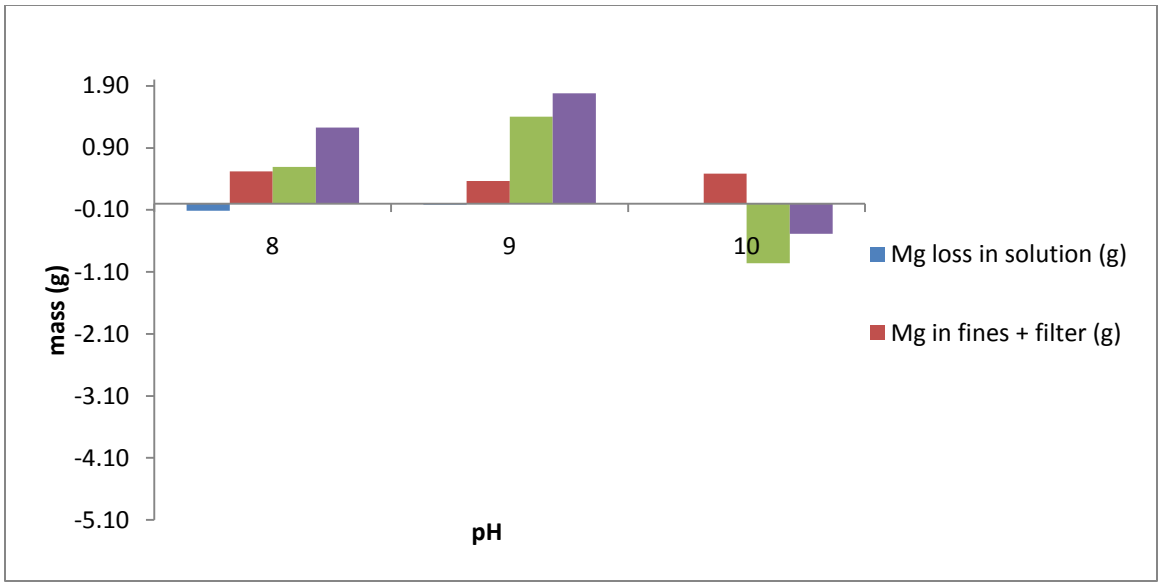

Figure D. 15 2009 magnesium mass balance @ T=140 for pH 8,9,10

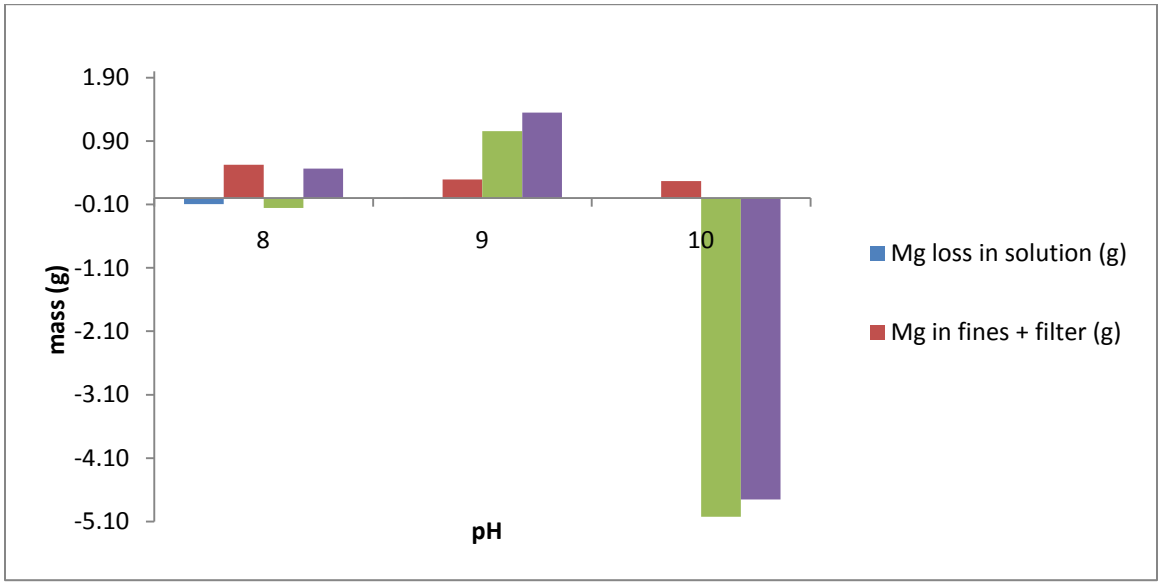

Figure D. 16 2009 magnesium mass balance @ T=160 for pH 8,9,10

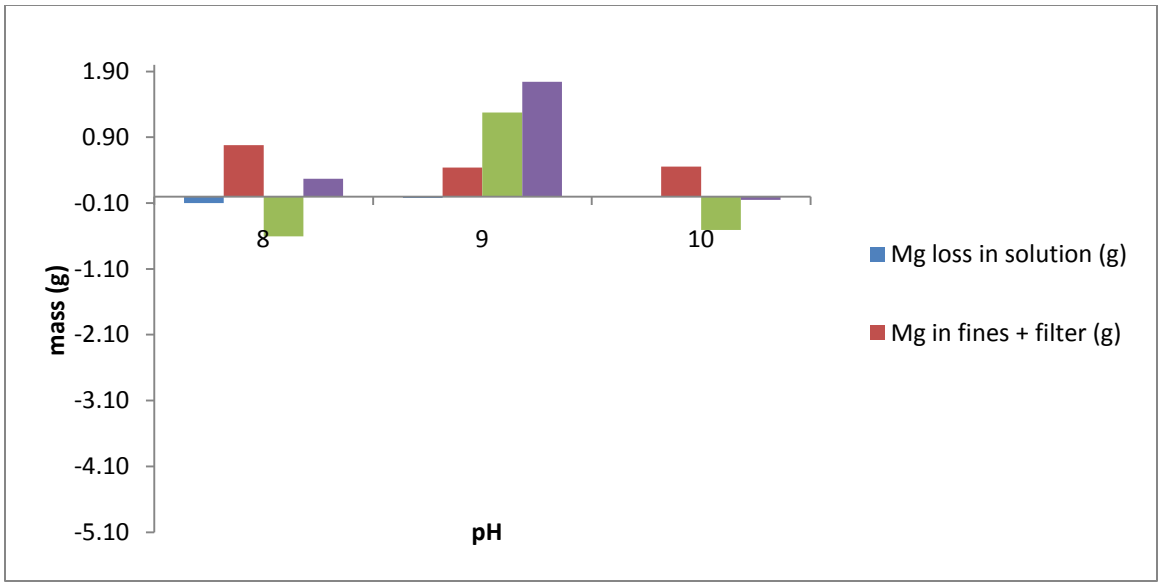

Figure D. 17 2009 magnesium mass balance @ T=180 for pH 8,9,10

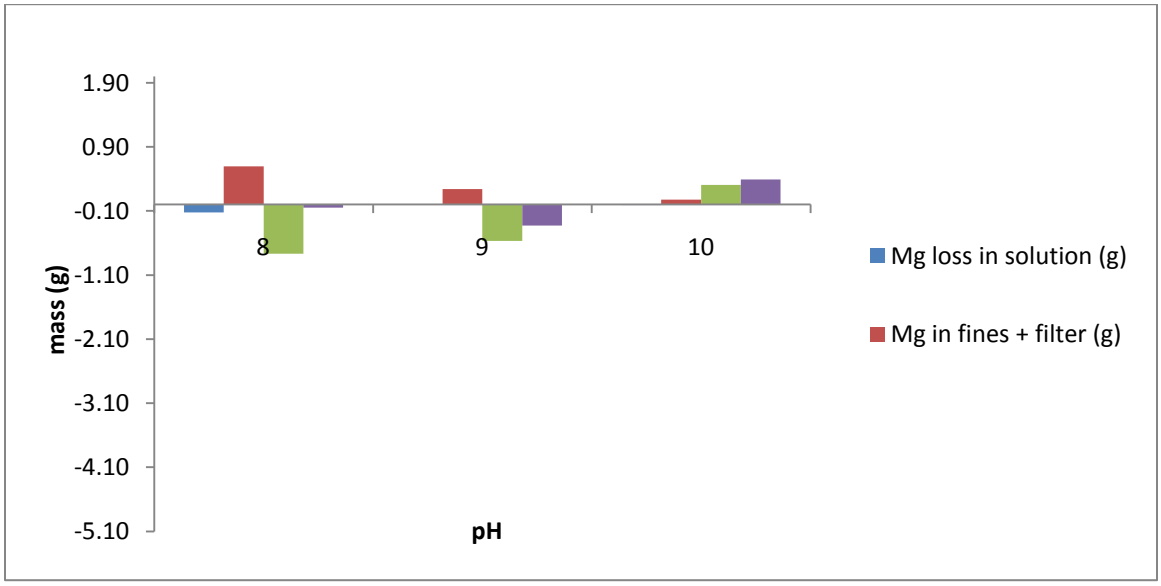

Figure D. 18 2009 magnesium mass balance @ T=200 for pH 8,9,10

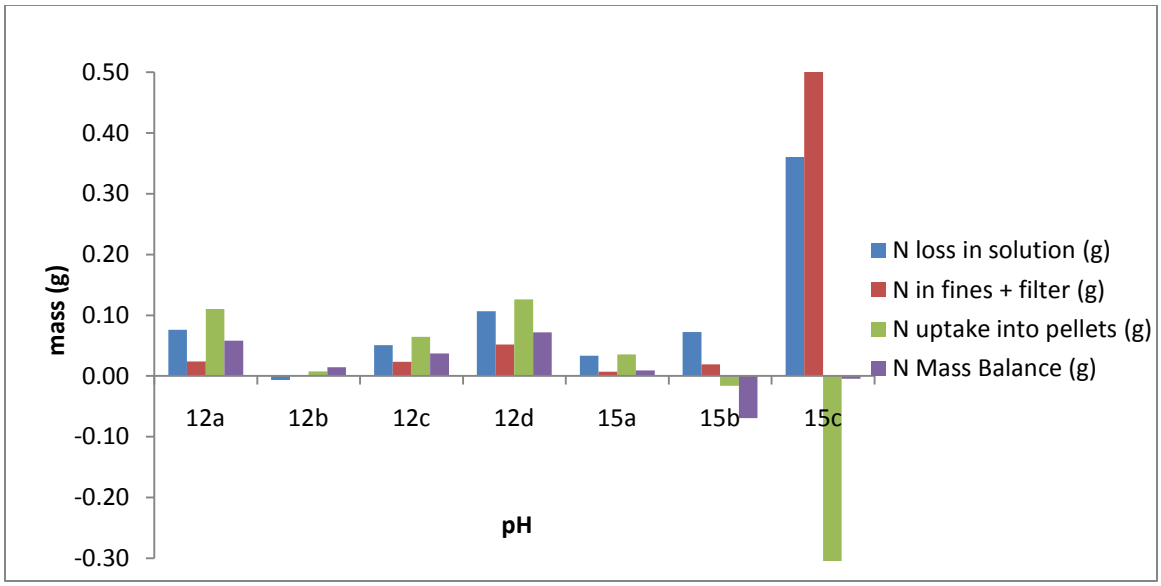

Figure D. 19 2010 nitrogen mass balance @ T=80

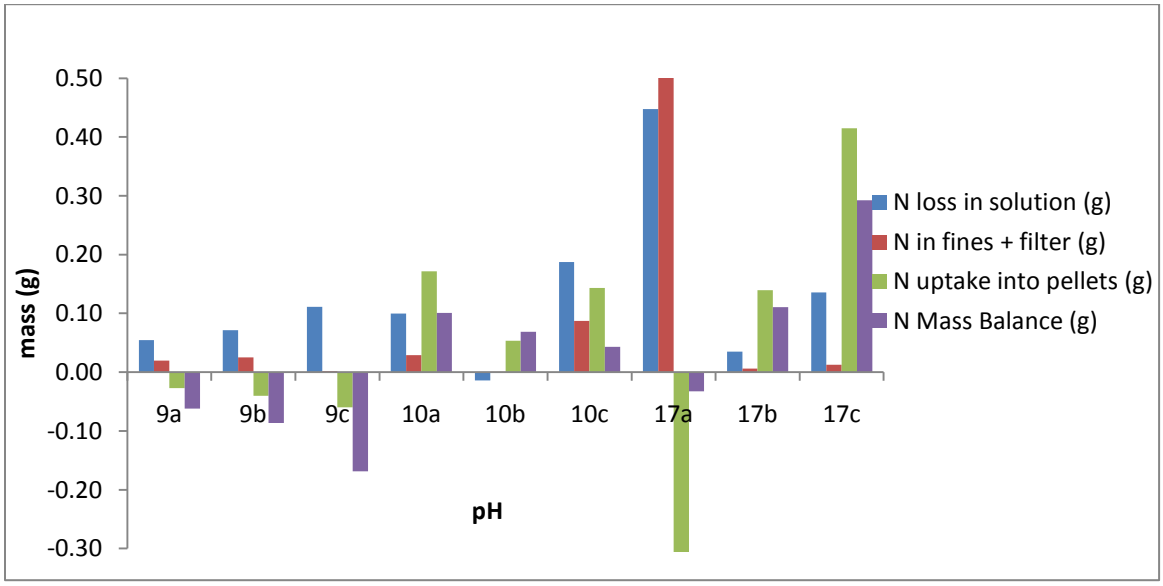

Figure D. 20 2010 nitrogen mass balance @ T=105

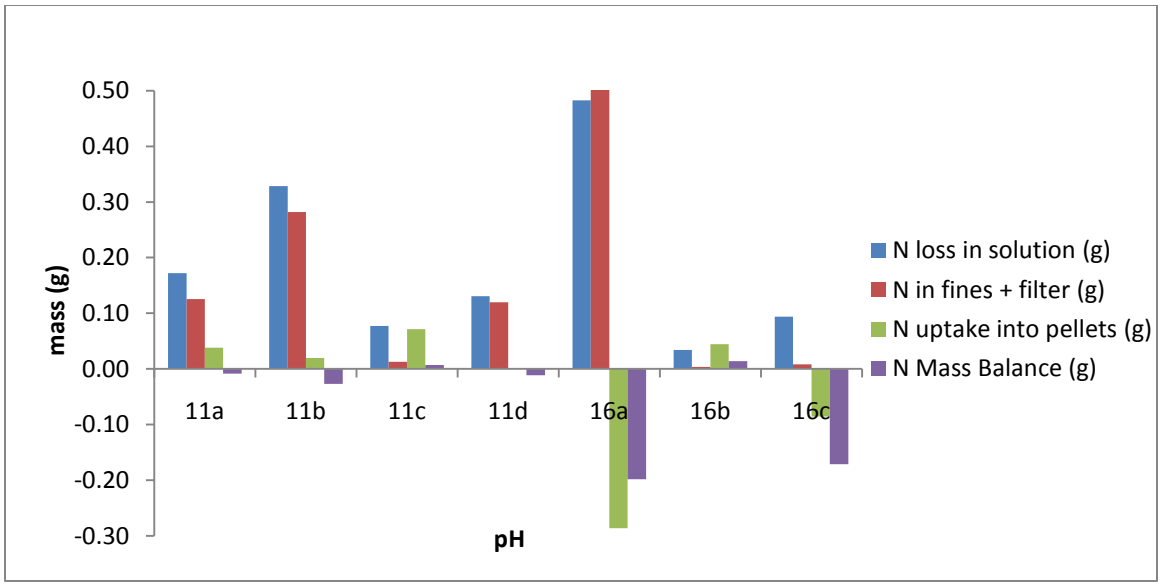

Figure D. 21 2010 nitrogen mass balance @ T=160

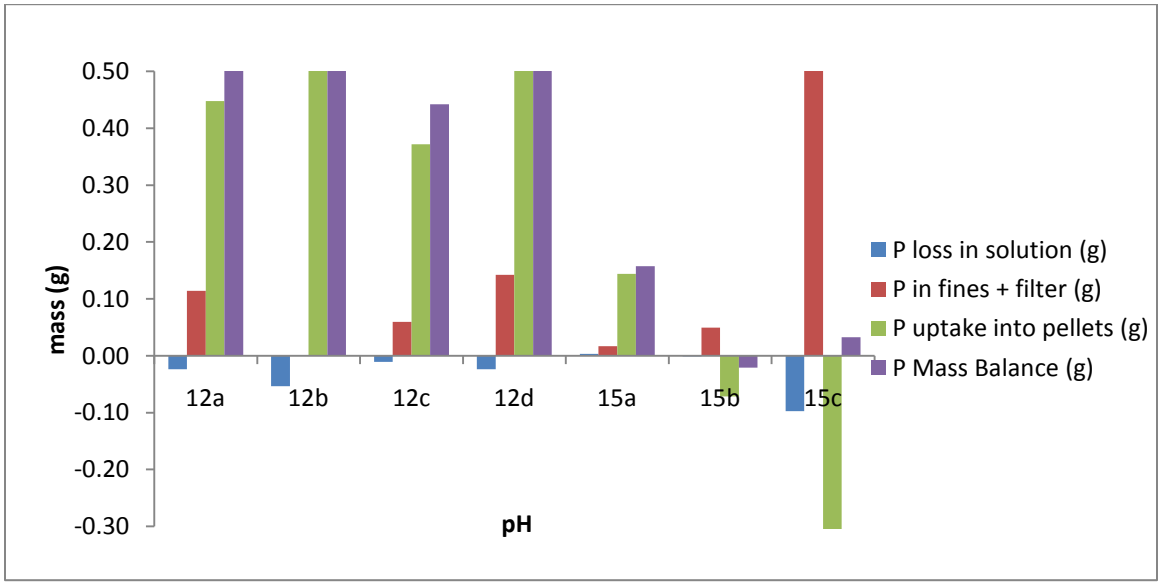

Figure D. 22 2010 phosphorus mass balance @ T=80

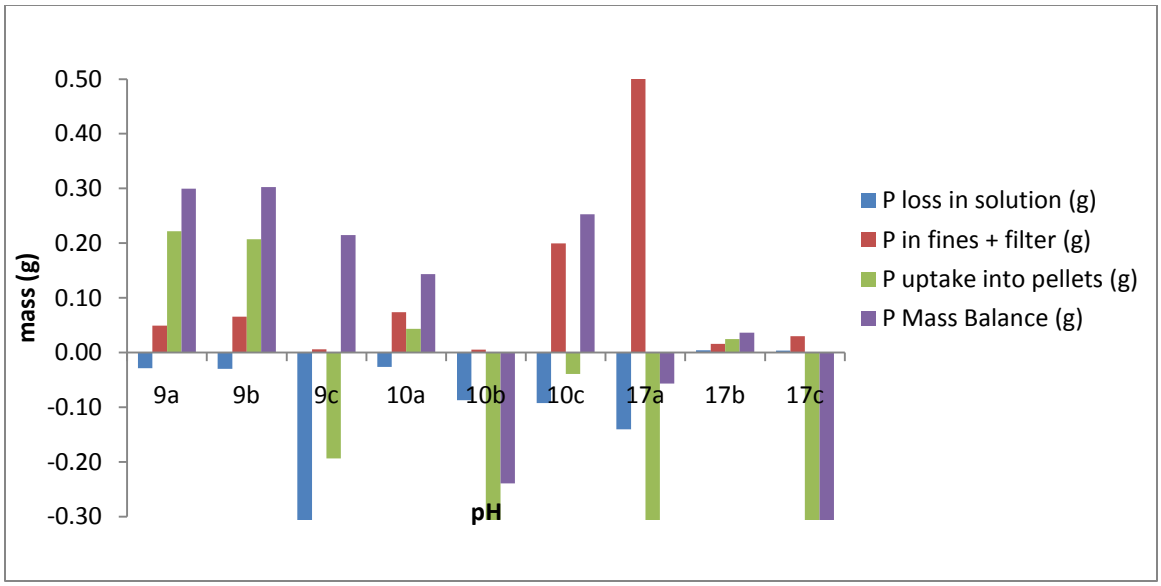

Figure D. 23 2010 phosphorus mass balance @ T=105

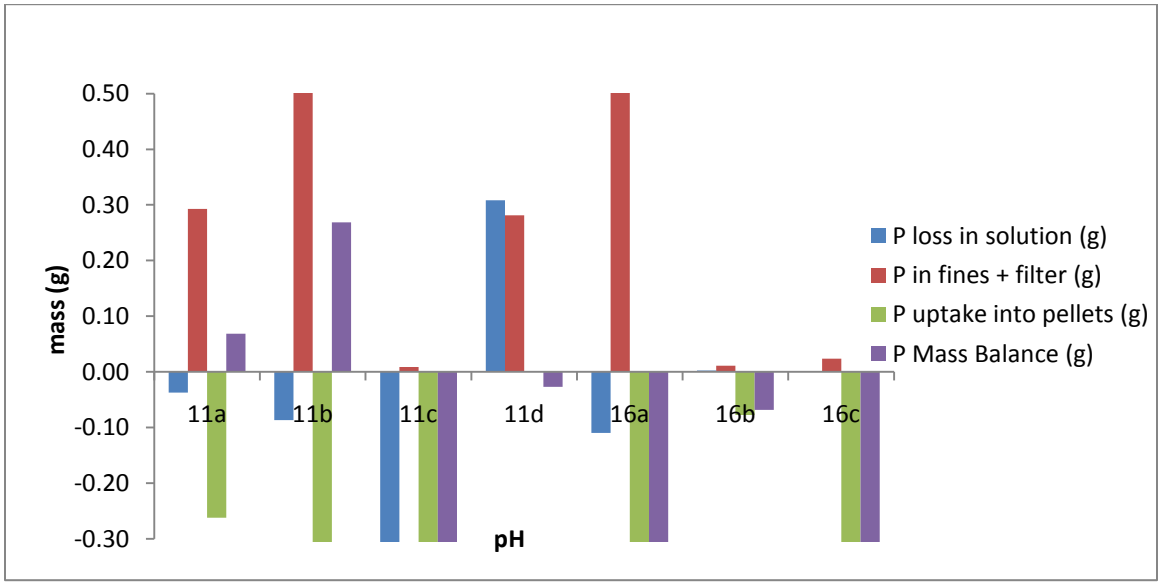

Figure D. 24 2010 phosphorus mass balance @ T=160

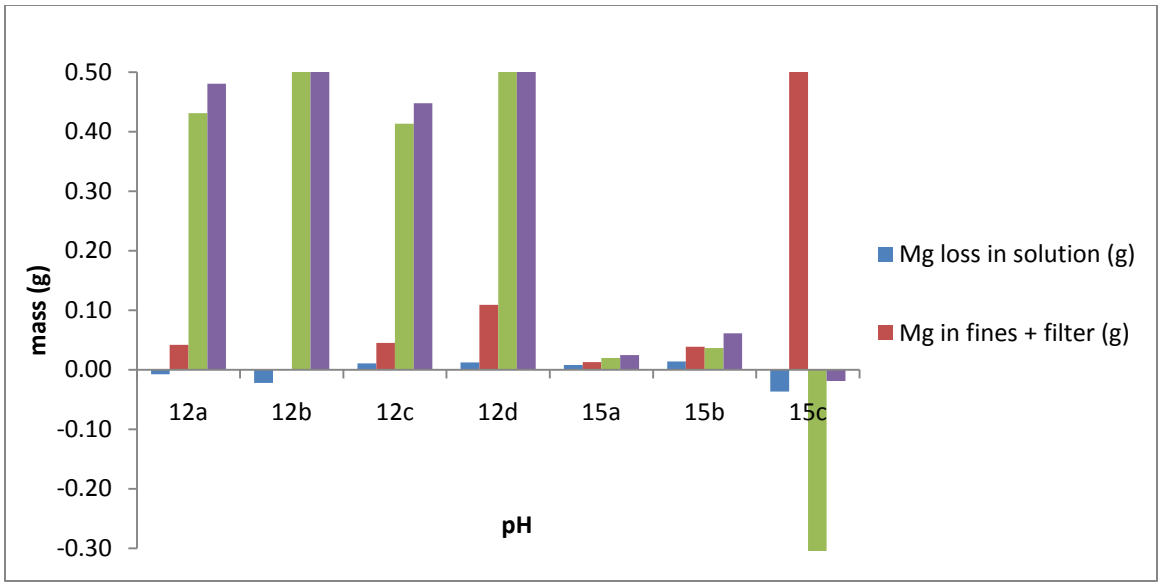

Figure D. 25 2010 magnesium mass balance @ T=80

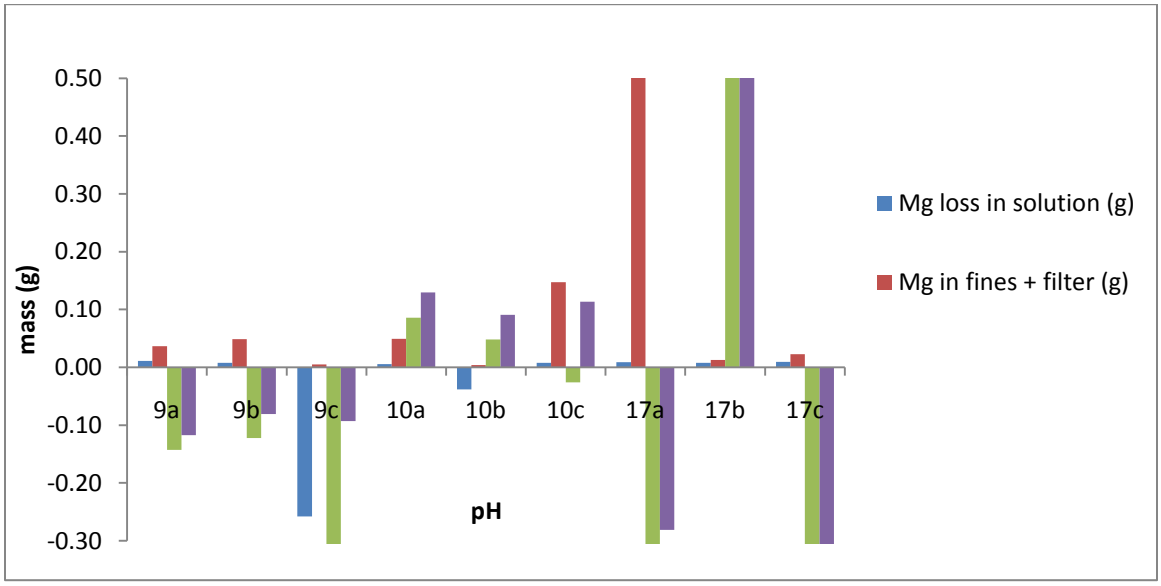

Figure D. 26 2010 magnesium mass balance @ T=105

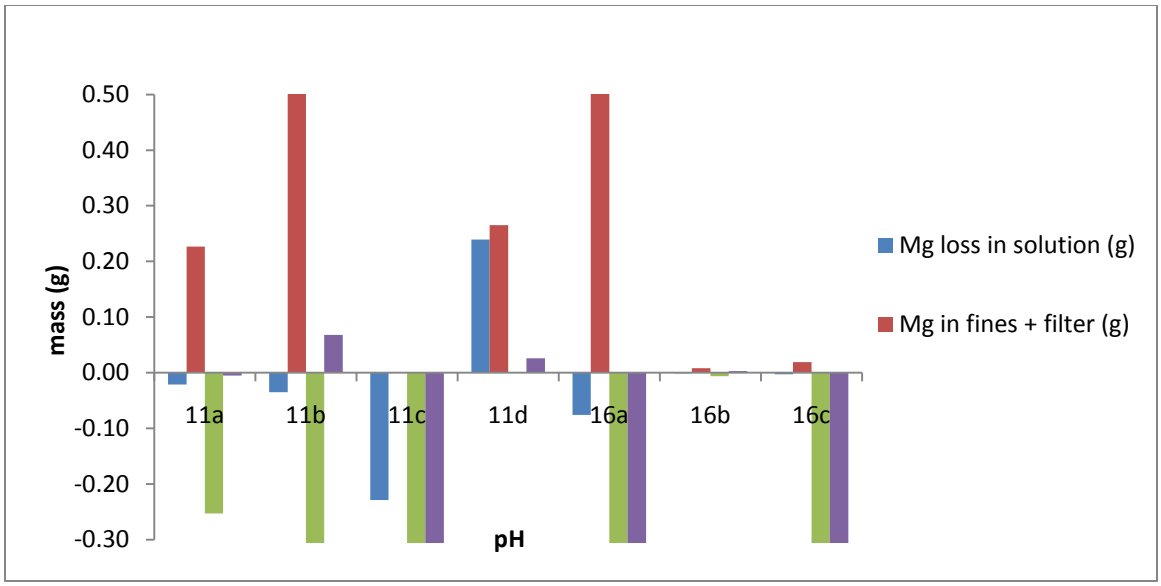

Figure D. 27 2010 magnesium mass balance @ T=160

Appendix E: Economic analysis

Table E. 1 Heating-reformation method

Struvite price ($/tonne)	3000
Struvite price ($/gram)	0.003
initial mass (g)	50
mass after heat (g)	28.5
mass after uptake (g)	43.3
Mass used per experiment (g)	5.2
Total Struvite cost per batch ($/batch)	0.01554
volume centrate per batch (L/batch)	0.5
Cost per litre ($/litre)	0.03108
Total volume wastewater per day (MLD)	76.2
BOD removed per day (lb/ML)	548.5986
Total volume centrate treated per day (L/Day)	54000
Sludge specific gravity	1.02
water unit weight (lb/ft3)	62.4
BOD utilization rate (lb cells/lb BOD utilized)	0.05
Volume sludge (cubic feet per day)	13135.75
volume centrate per volume sludge	0.75
Volume centrate (liters per day)	278973.8
Cost per day ($/day)	8670.505
Caustic price ($/kg)	0.5
Caustic usage (kg/L)	0.005773
Caustic price ($/L treated)	0.002887
Total caustic price per day ($/day)	805.3043
Electricity price ($/kwh)	0.02817
Power per volume (hp/L)	0.033333
power per volume (kilowatts/L)	0.02486
efficiency (%)	0.9
power drawn per day per litre	0.03
Daily power drawn per litre (kwh/day/l)	0.03
Daily Electricity cost ($/day)	217.07
Labour Cost	120.55
Total Cost per day ($/day)	9813

Table E. 2 Sidestream nitrification method

centrate NH3 conc (mg/L)	700
desired NH3 effluent conc (mg/L)	5
NH3 removal desired (mg/L)	695
molar mass NH3	17
molar mass N	14
N removal desired (mg/L)	572.3529
alkalinity consumption (eq CaCO3/mol N)	2
total alkalinity required (mg/L as CaCO3)	4088.235
alkalinity in centrate (mg/L as CaCO3)	100
alkalinity addition required (mg/L as CaCO3)	3988.235
Flow treated (L/day)	278973.8
daily mass CaCO3 requirmennt (kg/day)	1112.613
price CaCO3 ($/kg)	0.3
Daily alkalinity cost ($/day)	334
oxygen requirement (kg/day)	1620
oxygen price ($/kg)	0.2
Daily oxygen cost ($/day)	324
Total Cost per day ($/day)	658