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## Accepted Manuscript

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# Phosphate Recovery from Hydrothermally Treated Sewage Sludge using Struvite Precipitation

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## Abstract

New technologies are needed to recover phosphate from organic wastes, such as sewage sludge. Sewage sludge can be hydrothermally treated to make it safe but this process is expensive. Recovering a valuable by-product, such as phosphate, could improve the economics of hydrothermal treatment. Therefore, the technical and preliminary differential cost analysis of combining hydrothermal treatment with phosphate recovery (by precipitation of magnesium ammonium phosphate (struvite)) was investigated. The effects of pH, magnesium ion dose, and either wet oxidation or thermal hydrolysis hydrothermal treatment were examined. Phosphate recovery was more sensitive to pH than magnesium ion concentration, with diminishing rates of recovery at high levels of both. Also, more struvite was recovered following wet oxidation treatment than thermal hydrolysis. Preliminary differential cost analysis showed that wet oxidation combined with precipitation at an optimal pH and magnesium ion dose could generate revenue.

*Keywords:* Hydrothermal treatment; struvite precipitation; phosphate recovery; wastewater; sludge

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## 1. Introduction

Phosphate salts are valuable plant nutrients that regulate protein synthesis and facilitate both cell division and the development of new tissue (Barker & Pilbeam, 2015). As a result, phosphate is a key component of most fertilisers, and a sustainable supply of phosphates to plants is crucial for agricultural growth to feed an increasing world population. Phosphate salts used for fertilisers are currently derived from inorganic sources such as phosphate rock, and organic sources, such as urine and bone ash. Phosphate rock is currently the primary commercial source of phosphates used in fertilisers but the rate of extraction exceeds that of regeneration. Phosphate rock reserves have been estimated to be depleted in the next 40–100 years at the current extraction rate (Lewis, 2008; Ober, 2016; Reilly, 2007). Current organic sources of phosphate such as bone meal, and animal manure are not enough so new technologies need to be developed for sustainable phosphate recovery from other organic waste sources, such as sewage sludge.

Sewage sludge is produced in large quantities during wastewater treatment processes and is a source of phosphate and other nutrients but also various harmful compounds (Kelessidis & Stasinakis, 2012). Sewage sludge contains around 20% solids with the rest being water. The elemental and organic compositions of typical sewage sludge from New Zealand are given in Figure 1 (Baroutian et al., 2013a). The solids are mostly organic so the elemental analysis shows high levels of carbon (C), oxygen (O) and hydrogen (H). The next most abundant elements are nitrogen and phosphorus that could potentially be recovered and used to make valuable products. Approximately, 90 % of the phosphate in wastewater is trapped in the sludge solids (Blöcher et al., 2012) but the sludge cannot be used directly as a fertiliser, due to the presence of harmful heavy metals and other toxic compounds (Cieřlik et al., 2015). Therefore, some kind of treatment is required in order to make the solids safe, and make the nutrients recoverable.

Thermochemical and biological methods are currently the most commonly used treatments of sewage sludge. Thermochemical processes include combustion (also known as incineration), liquefaction, gasification, and pyrolysis (Furness et al., 2000). Combustion is less commonly used than in the past because it is now known that it can release both gaseous toxic compounds, such as dioxins and furans, and solid pollutants such as heavy metals (Kelessidis & Stasinakis, 2012). Liquefaction is a high-pressure and low-temperature process and is expensive and less commonly employed for sewage sludge treatment. Gasification mainly produces a single combustible gas as a product which is difficult to transport and can only be readily used locally. Acidic and alkaline leaching have also been used to treat sludge historically (Kalmykova & Karlfeldt Fedje, 2013). However, the final sludge still requires incineration and this process is costly, environmentally hazardous, and not energy efficient (Cieřlik et al., 2015). Biological methods include digestion (both aerobic and anaerobic) and composting (Furness et al., 2000; Fytli & Zabaniotou, 2008). However, these processes are time-consuming, require high levels of investment in commercial process vessels, have high energy requirements, are less efficient for not easily degradable organic materials, and require subsequent pasteurization for pathogen control (van Lier et al., 2001; Vandevivere, 1999).

Several methods exist for recovering phosphate, including physiochemical methods (precipitation in the form of struvite) (Jaffer et al., 2002), physical methods (nanofiltration, ion exchange) (Bottini & Rizzo, 2012; Schütte et al., 2015), and liquid-liquid extraction (Jiang & Mwabonje, 2009). Precipitation is the most commonly used method (Jaffer et al., 2002; Le Corre et al., 2007) because phosphate precipitates are safe to use as fertilizer (Jaffer et al., 2002). Precipitation of phosphate in the form of  $MgNH_4PO_4$  (struvite) is an attractive option because it can produce a hygienic, clean and pure product (Le Corre et al., 2009). Other methods have the disadvantages of multi-step processes, higher costs, and poorer product quality (Sartorius et al., 2011).

Hydrothermal treatment is emerging as an effective method not only to treat sewage sludge but also to release phosphate into the aqueous phase (Sartorius et al., 2011). Hydrothermal treatment involves heating a sewage sludge/water mixture to a sub-critical temperature (~150–320 °C) and pressure (~20–150 bar) in the presence of oxygen or nitrogen. The process is known as wet oxidation when oxygen is used and thermal hydrolysis when nitrogen is used (Hii et al., 2014). Hydrothermal treatment processes do not require chemical handling, are environmentally friendly, reduce the solids content substantially, reduce harmful heavy metals by concentrating them to smaller volume solid residue, and result in the release of nutrients (e.g. phosphate) from sewage sludge solids and production of other valuable by-products such as acetic acid and alcohols. There are two main shortcomings of hydrothermal treatments: (i) the high concentration of nutrients, such as phosphate, in the final product; and (ii) the high energy requirements of the process (Baroutian et al., 2016; Baroutian et al., 2015; Baroutian et al., 2013c; Debellefontaine & Foussard, 2000).

Hydrothermal treatments result in the release of phosphate from the solid phase into the liquid phase, and a further processing step is required to recover the phosphate.

The main objective of this work was to investigate the combination of hydrothermal treatment and struvite precipitation to make both processes more economically feasible when used together. Sewage sludge was hydrothermally treated using either wet oxidation or thermal hydrolysis. The effects of pH, magnesium ion dosage, and hydrothermal process type on phosphate recovery were investigated, and these parameters were modelled using response surface methodology (RSM), to capture both individual and interrelated effects. The fitness and significance of the developed models were investigated using analysis of variance (ANOVA). A basic assessment of the economics was used to investigate whether or not the combination of the two processes together would be beneficial for off-setting the costs of hydrothermal treatment.

## 2. Materials and Methods

### 2.1. Materials

Sludge samples were obtained from the Rotorua Lakes Council wastewater treatment plant, Rotorua, New Zealand. This material was analysed for  $\text{PO}_4^{3-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  using inductively coupled plasma mass spectrometry (ICP-MS). The  $\text{PO}_4^{3-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  initial concentrations of sludge prior to treatment were approximately 31, 90, 2.5 and 3.4 ppm, respectively. The sludge consisted of 40 % (v/v) primary and 60 % (v/v) secondary sludge. The sludge samples were frozen and stored at  $-20\text{ }^\circ\text{C}$  before being used. The frozen sludge samples were heated to  $\sim 4\text{ }^\circ\text{C}$  for each experiment and diluted with deionised water to 3 wt. % total solids, (typical for industrial scale hydrothermal treatment systems), and homogenised using a magnetic stirrer.

### 2.2. Hydrothermal treatment

Both wet oxidation and thermal hydrolysis processes were undertaken using a 1 L Parr Reactor (Series 4540 high-pressure reactor; Parr Instrument Company, USA). A diagram of the experimental set-up is shown in Figure 2.

For each experiment, the reactor was charged with 600 mL of sample sludge. For wet oxidation (WO), the reactor was initially pressurised to 30 bar using oxygen. Typical conditions used for wet oxidation in this study were a temperature of  $220\text{ }^\circ\text{C}$ , a mixing speed of 500 rpm, and a 60 min reaction time. The selected temperature was in the median range typically used for wastewater treatment applications. For thermal hydrolysis (TH), the reactor was initially pressurised to 30 bar using nitrogen, at a temperature of  $180\text{ }^\circ\text{C}$ , mixing speed of 500 rpm, and a reaction time of 60 min. The selected conditions of WO and TH were based on optimal conditions determined from previous studies (Baroutian et al., 2013c; Prince-Pike

et al., 2015; Yousefifar et al., 2017), and are typical of the conditions used for industrial applications (Hii et al., 2014).

### 2.3. Phosphate recovery

Phosphate was recovered by adding  $\text{MgCl}_2$  solution to facilitate precipitation of struvite. A 1000 ppm  $\text{MgCl}_2$  solution was prepared by dissolving the required amount of  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$  in deionized water. All reagents used were of analytical grade and solutions were stored at  $4^\circ\text{C}$ . For each experiment, the solution pH and magnesium ion dose ranges were prepared based on the conditions set out in Table 1. The solution pH was adjusted to 9.0 by dropwise addition of 1.0 M NaOH at the beginning of each experiment. All experiments were carried out at room temperature.

A 15 mL liquid sample was taken at the end of each 2h reaction. Two drops of concentrated HCl were added immediately, and the sample was stored in the refrigerator at  $4^\circ\text{C}$  prior to elemental analysis by ICP-MS. The precipitates formed during the experiments were collected via filtration and oven dried for twelve hours at  $35^\circ\text{C}$ . Precipitated material was re-dissolved in a solution containing 1 mL concentrated HCl and 9 mL deionized water prior to  $\text{NH}_4^+$  and  $\text{PO}_4^{3-}$  analysis by ICP-MS. Experimental error was assessed by carrying out replicate experiments at the designed centre points, as discussed in Section 2.4.

### 2.4. Design of experiments for response surface methodology modelling

A face-centered central composite (FC-CCD) design of response surface methodology (RSM) was used to investigate the individual and interrelated effects of pH, magnesium ion dosage and hydrothermal treatment process type (WO or TH) on phosphate recovery, whilst



minimizing the number of experiments required. For each hydrothermal process type (WO or TH), a total of 11 experiments provided 4 factorial, 4 axial, and 3 replications of the centre point as shown in Table 1. The experiments at the centre points were repeated in triplicate to identify the broadest possible region where the standard error of prediction remained relatively consistent. Design-Expert<sup>®</sup> software (State-Ease Inc., USA) was used to build empirical models to predict optimal phosphate recovery.

### 2.5. Regression modelling and analysis of variance

Experimental data from 22 experiments were used to develop second-order-quadratic response models for WO and TH. The model results were compared with experimental results using analysis of variance (ANOVA) using Design-Expert<sup>®</sup> software to determine  $p$ -value ( $p$  = probability), lack of fit, and regression coefficients ( $R^2$ ). The  $p$ -value is the probability of getting a result equal to or more than the experimental result (Box et al., 1978). A  $p$ -value less than 0.05 indicates a strong evidence of significant model or significant effect. Lack of fit indicates the difference between regression function fit and the data. A lack of fit  $p$ -value less than 0.10 was used to determine that the model fitted the data. The regression coefficient ( $R^2$ ) shows the ‘goodness’ of fit of the fitted regression line with the data. The effect of individual variables on phosphate recovery from the hydrothermally treated sewage sludge and their interactions were also evaluated using linear perturbation analysis. The slope of a factor on the perturbation plot shows the sensitivity of the response to that factor (Bonnans & Shapiro, 2013).

## 3. Results and Discussion

### 3.1. Recovery of struvite and composition of sludge pre- and post- treatment

The  $\text{PO}_4^{3-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  concentrations of sludge prior to treatment were approximately 31, 90, 2.5 and 3.4 ppm respectively. After treatment, the sludge contained 0–90 %, 30–37 %, 11–50 %, and 15–20 %  $\text{PO}_4^{3-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  respectively.

### 3.2. RSM, regression modelling and analysis of variance

The results of the 22 experiments, shown in Table 1, were used to develop a series of quadratic response models. Equations (1) and (2) represent the quadratic response models of the WO and TH processes respectively, for phosphate recovery in terms of the investigated parameters. The quadratic models relate phosphate recovery to the system pH ( $A$ ) and magnesium ion dose ( $B$ ). Diagnostics of the residuals between the predicted and actual phosphate recovery values showed that no transformation was needed to improve the phosphate recovery models.

$$P(\text{WO}) = -998.31 + 211.92 A + 0.9 B - 0.107 AB - 10.79 A^2 + 2.91 E^{-4} B^2 \quad (1)$$

$$P(\text{TH}) = -892.62 + 197.53 A + 0.91 B - 0.107 AB - 10.79 A^2 + 2.91 E^{-4} B^2 \quad (2)$$

where,  $A$  = pH,  $B$  = magnesium ion dose (as mL of 1000 ppm  $\text{MgCl}_2$  solution), and  $P(A, B)$  = phosphate recovery (ppm).

A comparison of the modelled results with the actual phosphate recovery shows that the model has a correlation coefficient of  $R^2 = 0.965$ , and thus is able to explain the variation adequately.

The ANOVA results for the response model are presented in Table 2, and show that most of the factor  $p$ -values were less than 0.0001 and the  $p$ -value testing a lack of model fit was less than 0.1. These results show that the quadratic models fit the experimental data well. The

ANOVA results in Table 2 show that the pH (*A*), magnesium ion dosage (*B*), and process type (*C*) were all significant factors for the rate of phosphate recovery, as their *p*-values were less than 0.05.

The increase in phosphate recovery due to increased magnesium ion dosage is due to the equilibrium shifting to the right of the struvite formation reaction, as shown by Equation (3) while the solubility of struvite decreases with an increasing pH, thus increasing precipitation (Doyle & Parsons, 2002). However, in addition to this, the increase in phosphate recovery at higher pH values may also be due to competing reactions that favour lower pH, such as the formation of CaHPO<sub>4</sub> as shown by Equation (3). Higher pH may lower the competition for phosphate between struvite and calcium phosphate.



Calcium phosphate formation is likely due to the presence of calcium ions in the sludge. Along with the MgNH<sub>4</sub>PO<sub>4</sub>, fourteen other salts were produced under similar conditions, including MgHPO<sub>4</sub> (Equation (4)), Mg(OH)<sub>2</sub> (Equation (5)), and CaHPO<sub>4</sub> (Equation (6)) (Mohan et al., 2011). However, at the given conditions, the formation of MgNH<sub>4</sub>PO<sub>4</sub> is most favourable because other reactions, such as MgHPO<sub>4</sub> formation, occur at pH values less than 6 (Musvoto et al., 2000). Similarly, the rate of Mg(OH)<sub>2</sub> formation is slow (> 1 day) compared with struvite formation (Mamais et al., 1994) and requires higher pH (Musvoto et al., 2000). The formation of CaHPO<sub>4</sub> is suppressed by the presence of magnesium ions (Çelen et al., 2007).

The interaction between pH and magnesium ions was also found to be significant, Table 2. Perturbation plots showing the influence of varying pH (*A*) and magnesium ion dose (*B*) on the phosphate recovery response for each process type are shown in Figure , and these plots highlight the factor(s) that phosphate recovery is most sensitive to (based on slope steepness). The results in Figure show that phosphate recovery after WO process is more sensitive to pH (*A*) than magnesium ion dosage (*B*). Process type was also found to be a significant factor in the model, Table 2, with the struvite recovery rate significantly higher using WO than TH. It is hypothesised that process type affects the phosphate recovery rate because WO results in faster phosphate solubilisation from the solids than for TH (Baroutian et al., 2013b). Faster phosphate solubilisation is probably also the reason why there was significant interaction between the pH and process type (Table 2), with the recovery of phosphate being more sensitive to pH in the WO than the TH process. Struvite solubility decreased as pH increased. However, if more phosphate is solubilised out of the solids during WO then there is more phosphate available to be recovered so pH would have a larger impact on recovery. It is important to note that the relationship between pH and magnesium ion dose means that that a high value of one factor decreases the effect of the other on phosphate recovery, i.e. there is a diminishing return of using high doses of both magnesium ions and pH simultaneously, Figure . This result is particularly relevant for industrial application, as chemical dosing is expensive, and suggests that only one of the two factors (pH or magnesium ion dosage) would need to be controlled at any time.

### 3.3. Preliminary analysis of integration of phosphate recovery with hydrothermal treatment

The standard wastewater treatment process is illustrated in Figure (a). The two key operating costs for the standard process are the use of ethanol as a source of organic material for biological treatment, followed by the substantial cost of sending the large quantity of sludge produced to landfill. Incorporation of hydrothermal treatment into the standard process offers the substantial benefit of 90–95% reduction of the volume of waste sent to landfill, and eliminates the use of ethanol as a source of organic material for biological treatment, as the liquid product can be used as a substitute (Figure (b)). However, hydrothermal treatment has very high energy operational costs. Phosphate recovery can be integrated into the process to offset some of the operational costs, Figure (c).

This work is preliminary, so a full economic analysis cannot be carried out yet. However, an assessment can be made on whether phosphate recovery can be used to offset at least some of the cost hydrothermal treatment, whilst being of environmental benefit at the same time.

A comparison can be made of the major operational cost differences between scenarios (b) and (c) in Figure , i.e. between using hydrothermal without and with phosphate recovery, respectively.

1. Struvite precipitation requires pH adjustment, which is an additional cost. The estimated cost of pH adjustment with NaOH is NZ\$616/tonne (Xia et al., 2016).
2. Struvite precipitation requires magnesium ion dosing, another additional cost. However, a low-cost source of magnesium ions can be used, such as MgO, which costs NZ\$787/tonne (Shunli et al., 2016).
3. Struvite can be sold as slow-release fertiliser, and the income that could be generated is estimated to be around NZ\$780/tonne (Shu et al., 2006).

The amounts of sodium hydroxide and magnesium oxide required were obtained from the experimental data presented in Table 1, and are also a function of the hydrothermal treatment

used. As a variety of experimental conditions were used, a range of results for the loss or income due to different struvite precipitation scenarios are presented in Table 3.

The income generated from struvite production must at least cover the cost of the chemicals needed for the process in order to be favourable for integration with hydrothermal treatment. The loss or income from incorporating phosphorus recovery has been assessed using the following formula per 100 m<sup>3</sup> of sludge treated,

$$\text{Loss or Income} = \$780 \times M_S - \$616 \times M_{NaOH} - \$787 \times M_{MgO} \quad (7)$$

where  $M_S$  is the mass of struvite (t) recovered from 100 m<sup>3</sup> of hydrothermally treated sludge,  $M_{NaOH}$  is the mass of sodium hydroxide (t) required to adjust the pH and  $M_{MgO}$  is the mass of magnesium oxide (t) required for the struvite precipitation.

This preliminary analysis only includes the costs of chemicals and does not include the costs of energy usage, chemical recovery or initial capital costs. However, it is useful for comparing differences among treatments and drawing conclusions about whether phosphate recovery can be synergistic with hydrothermal treatment. It is thus a preliminary differential cost analysis.

The most cost effective conditions for struvite recovery was using a WO process followed by precipitation at a pH of 9 with a minimum magnesium ion dosing level, Table 3. In this case, the net income would be approximately NZ\$14.95/100 m<sup>3</sup> of sludge. In contrast, the use of thermal hydrolysis had limited cost benefits, Table 3. Therefore, the integration of struvite precipitation with wet oxidation is potentially economically favourable, a novel finding of this work. Further work is required in order to carry out a full economic analysis that includes the benefit of reduced landfill costs and elimination of ethanol for biological treatment due to

the hydrothermal process, as well as accounting for the high energy and maintenance costs of hydrothermal treatment. It appears that the quantity of struvite recovered needs to be at least around 11 kg/100 m<sup>3</sup> before the treatment becomes favourable.

#### 4. Conclusions

Comparison of two types of hydrothermal treatment to degrade solids showed that more phosphate was recovered with wet oxidation than thermal hydrolysis. Phosphate recovery increased with increasing pH and magnesium ion dosing, however these factors interacted and there was a diminishing rate of return with increasing the levels of both together. A preliminary integration analysis showed that a combination of wet oxidation and struvite precipitation could generate income to off-set energy costs of the wet oxidation process.

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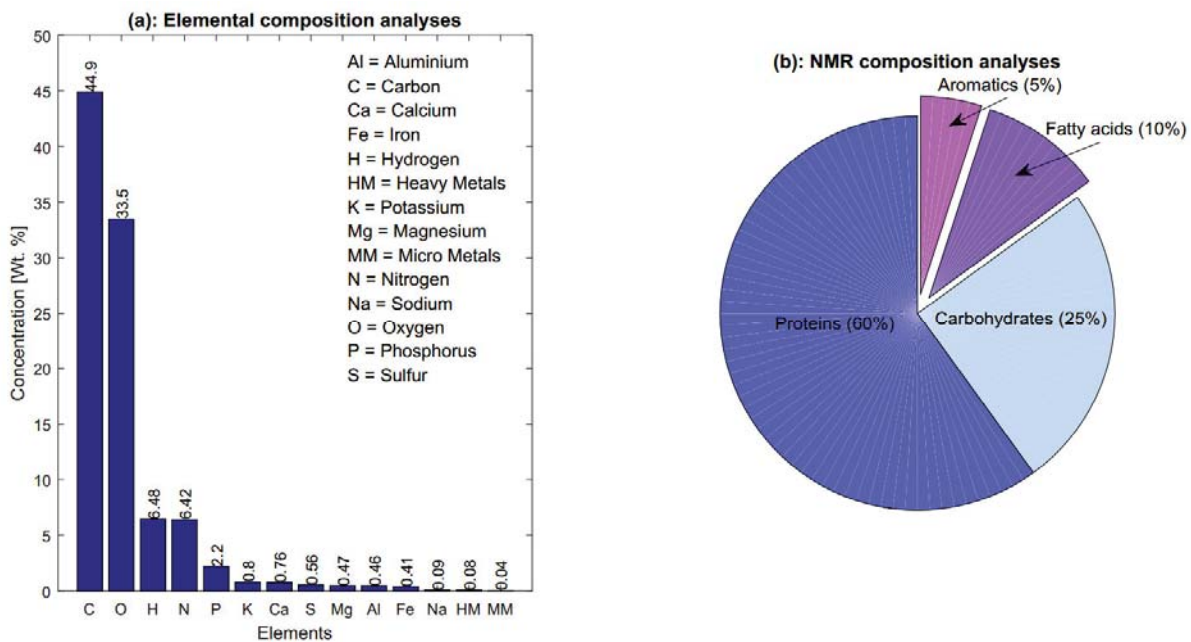


Figure 1. Elemental and  $^{13}\text{C}$  Nuclear Magnetic Resonance (NMR) composition analyses of sewage sludge (data adapted from (Baroutian et al., 2013a))

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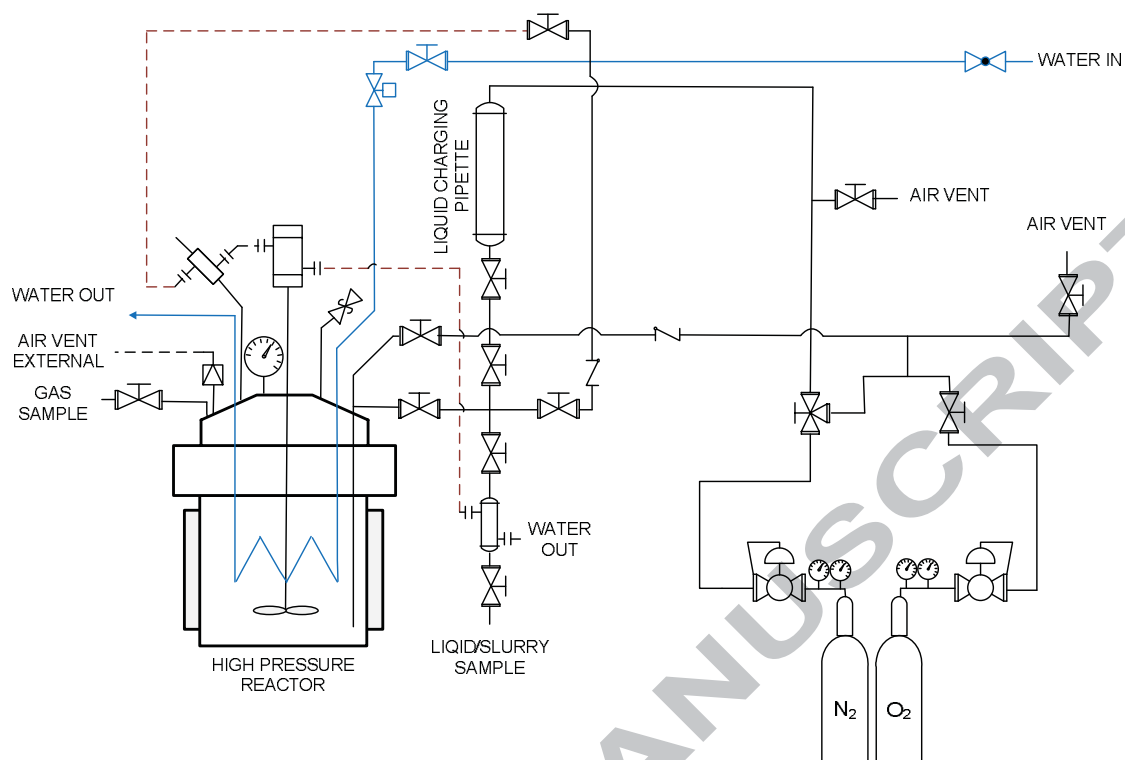


Figure 2. Hydrothermal treatment experiment set-up schematic

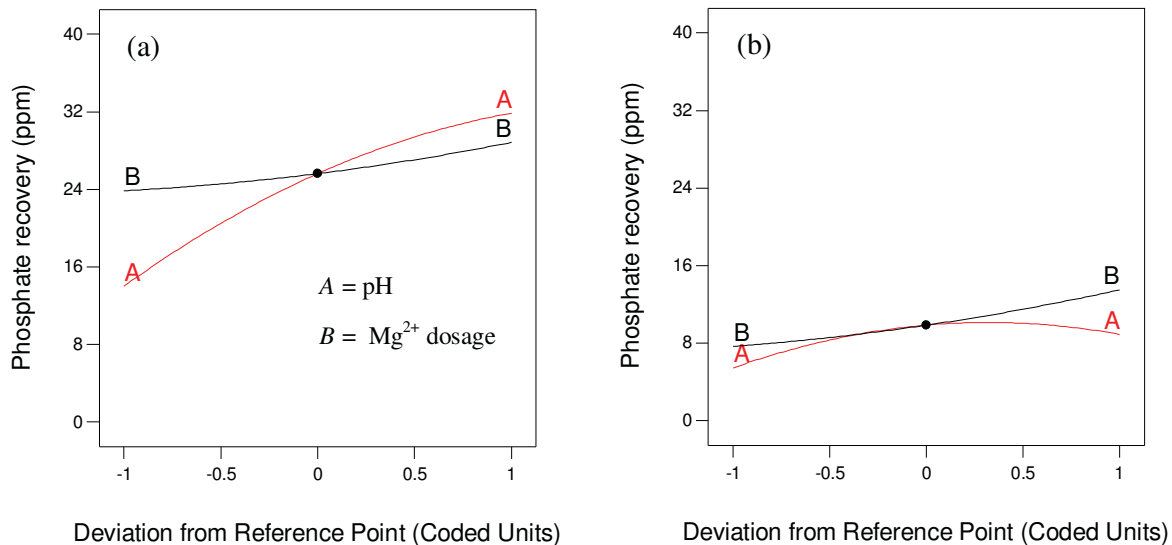


Figure 3. Perturbation curves showing the influence of varying factors (A = pH, and B = Mg<sup>2+</sup> dosage) on the phosphate recovery of WO (a) and TH (b) of sewage sludge

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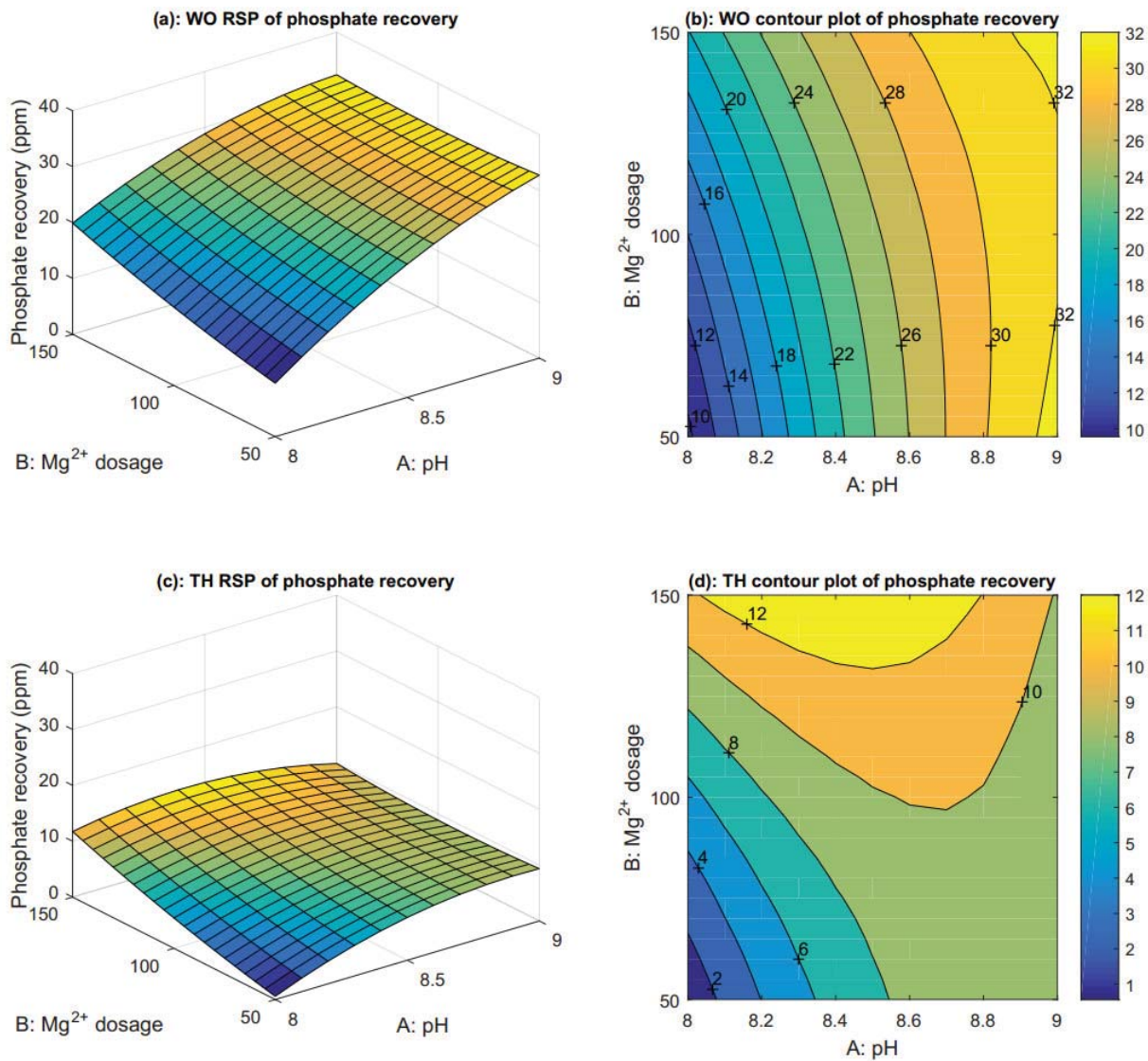


Figure 4. Response surface plot (RSP) of phosphate recovery

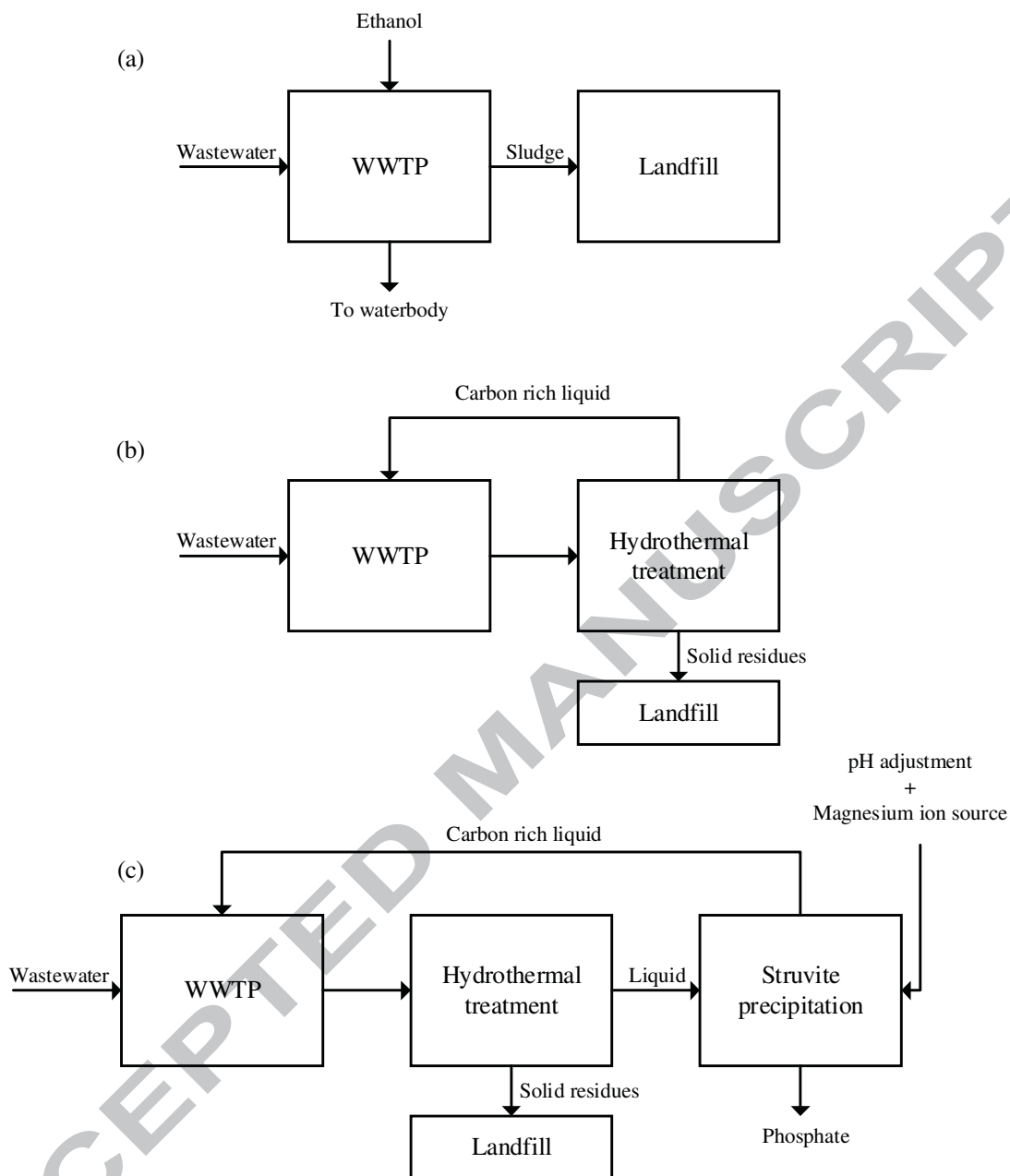


Figure 5. Diagrams showing the various options for a wastewater treatment plant (WWTP):

(a) standard WWTP; (b) WWTP with hydrothermal treatment; and (c) WWTP with a combination of hydrothermal treatment and phosphate recovery



Table 1. Experimental design matrix and response values for wet oxidation (WO) and thermal hydrolysis (TH). The order of the experiments was randomised when carrying out the laboratory work

Point type	Variable 1: pH	Variable 2: Magnesium ion dosage (mL of 1000 ppm MgCl <sub>2</sub> solution)	Variable 3: process type	Response 1: Phosphate recovery (ppm)
Factorial	8	50	WO	8.1
Factorial	9	50	WO	31.2
Factorial	8	150	WO	20.3
Factorial	9	150	WO	31.2
Axial	8	100	WO	11.6
Axial	9	100	WO	31.2
Axial	8.5	50	WO	26.4
Axial	8.5	150	WO	29.1
Centre	8.5	100	WO	25.6
Centre	8.5	100	WO	28.5
Centre	8.5	100	WO	27.0
Factorial	8	50	TH	3.2
Factorial	9	50	TH	12.0
Factorial	8	150	TH	11.8
Factorial	9	150	TH	11.5
Axial	8	100	TH	6.3
Axial	9	100	TH	8.0
Axial	8.5	50	TH	2.9
Axial	8.5	150	TH	12.4
Centre	8.5	100	TH	8.6
Centre	8.5	100	TH	10.6
Centre	8.5	100	TH	9.2

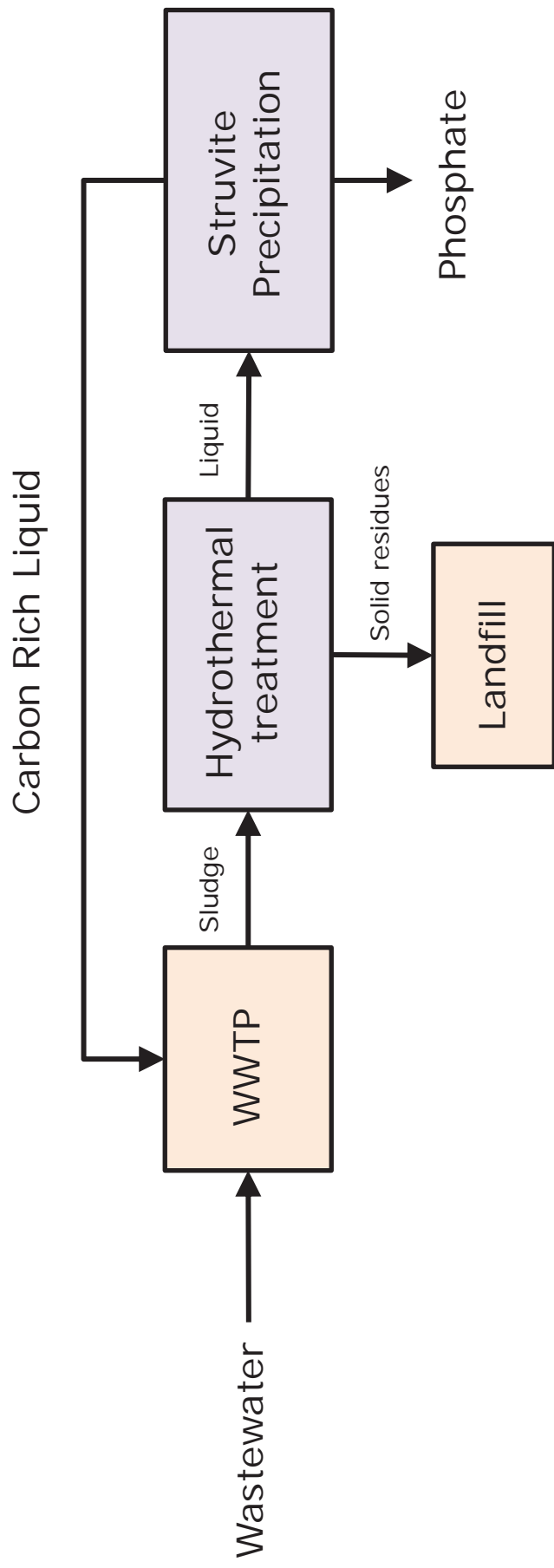
Table 2. Quadratic model ANOVA results with  $R - \text{Squared} = 0.974$ 

Source	$F - \text{value}$	$p - \text{value}$	Remarks
Model	61.11	< 0.0001	Significant
$A - pH$	59.72	< 0.0001	Significant
$B - Mg^{2+} \text{ dosage}$	15.39	0.0018	Significant
$C - \text{process type}$	369.93	< 0.0001	Significant
$AB$	9.99	0.0075	Significant
$AC$	27.25	0.0002	Significant
$BC$	0.095	0.7626	Not significant
$A^2$	6.47	0.0245	Significant
$B^2$	0.47	0.5046	Not significant
Lack of fit	4.89	0.0705	Not significant

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Table 3. Differential cost analysis of adding a struvite precipitation step after hydrothermal treatment of sludge

<b>Struvite precipitation combined with wet oxidation</b>							
<b>pH</b>	<b>Struvite kg/100 m<sup>3</sup></b>	<b>NaOH kg/100 m<sup>3</sup></b>	<b>MgO kg/100 m<sup>3</sup></b>	<b>Struvite income NZ\$/100 m<sup>3</sup></b>	<b>NaOH Cost NZ\$/100 m<sup>3</sup></b>	<b>MgO Cost NZ\$/100 m<sup>3</sup></b>	<b>Income or Loss NZ\$/100 m<sup>3</sup></b>
9	24.7	2.5	3.53	19.26	1.5	2.77	<b>14.95</b>
8.5	20.9	1.9	3.53	16.3	1.2	2.77	12.37
9	24.7	2.5	7.05	19.26	1.5	5.55	12.17
8.5	22.6	1.9	7.05	17.63	1.2	5.55	10.92
8	9.2	1.3	7.05	7.15	0.8	5.55	<b>0.83</b>
<b>Struvite precipitation combined with thermal hydrolysis</b>							
9	9.5	1.9	3.53	7.44	1.2	2.77	<b>3.51</b>
8.5	8.4	1.9	7.05	6.53	1.2	5.55	-0.17
8	5.0	1.90	7.05	3.87	1.2	5.55	<b>-2.83</b>



## Highlights:

- Struvite crystallisation was used to recover phosphorus from sludge after WO and TH.
- Phosphorus recovery was found to be more sensitive to pH than magnesium dosage.
- More phosphorus was recovered after WO than TH.
- Economically WO is more suited for being paired with struvite crystallisation.

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