STRUVITE PRECIPITATION FOR THE RECOVERY OF AMMONIUM NITROGEN FROM LANDFILL LEACHATE

MOHAMAD S J DARWISH

UNIVERSITI TEKNOLOGI MALAYSIA

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MOHAMAD S J DARWISH

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Universiti Teknologi Malaysia

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To my beloved parents, brother and sisters

To my elder brother Yahya … Mercy of Allah be upon him

To my lovely wife, Dr. Shaymaa Mustafa, and sons, Yahya and Omar

To my country … Palestine

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ABSTRACT

Struvite ($MgNH_4PO_4.6H_2O$, MAP) precipitation is an effective method to recover ammonium nitrogen (NH_4-N) from wastewater into a valuable and environmental friendly material. It is crystallized by a chemical reaction between NH_4-N, Mg and P, which is affected by several factors, mainly pH, molar ratios, foreign ions and mixing intensity (*G*). Landfill leachate (LL) contains high concentration of NH_4-N that should be treated properly to avoid the environmental pollution problems. Therefore, the aim of this study is to develop a sustainable approach for NH_4-N recovery from municipal LL via MAP precipitation technology. The study investigated a low-cost P source, optimized NH_4-N recovery in terms of pH, Mg:N, K:N and *G*, studied the effect of organic matter and determined the effect and sorption mechanism of cadmium (Cd) and nickel (Ni) during MAP precipitation. Three types of waste bones were tested for low-cost P source; fish, chicken and cow waste bone ash. Fish bone ash contained the highest P content (17% wt.). The P extraction by acidic leaching was optimized by Response Surface Methodology (RSM) and the results showed that applying 2M H_2SO_4 and 1.25 kg H_2SO_4/kg ash resulted with extracting 95% of P. The extracted P solution (150 g-P/L) was applied successfully in MAP precipitation. Recovery of NH_4-N in synthetic LL was optimized by RSM. Maximum NH_4-N recovery (90%) was achieved at pH 8.5, Mg:N = 1.25, K:N = 0.1 and $G = 95\ s^{-1}$. The effect of organic matter on MAP recovery was determined using synthetic and actual LL (filtered and unfiltered). Propionic, butyric and acetic acids formulated the organic content in synthetic LL, in which an insignificant effect was noticed with minor removal of total organic carbon (TOC) (6.30-13.96%). For actual LL, NH_4-N recovery efficiencies were 93%, 71% and 28% using $MgCl_2$+Na_2HPO_4, MgO+P solution and MgO+Na_2HPO_4, respectively. It was also found that Cd and Ni were co-precipitated with MAP, forming struvite analogues, which could affect the purity of MAP. Sustainability of NH_4-N recovery has to be further improved to be efficient for large-scale applications of LL treatment.

ABSTRAK

Pemendakan struvit ($MgNH_4PO_4.6H_2O$, MAP) merupakan satu kaedah yang berkesan untuk perolehan semula nitrogen ammonia (NH_4-N) daripada air sisa kepada bahan yang berharga dan mesra alam. Ia membentuk kristal melalui tindak balas kimia di antara NH_4-N, Mg dan P, yang dipengaruhi oleh beberapa faktor, terutamanya pH, nisbah molar, ion-ion luaran dan keamatan pembauran (*G*). Air larut lesap daripada tapak pelupusan sisa pepejal (LL) mengandungi NH_4-N pada kepekatan tinggi yang perlu dirawat dengan baik untuk mengelakkan masalah pencemaran alam sekitar. Oleh itu, tujuan kajian ini adalah untuk membentuk satu kaedah mampan bagi memperolehi NH_4-N daripada LL menggunakan teknologi pemendakan MAP. Kajian ini mengkaji satu sumber P berkos rendah, mengoptimumkan perolehan NH_4-N dari aspek pH, Mg:N, K:N dan *G*, mengkaji kesan bahan organik dan menentukan kesan dan mekanisma jerapan kadmium (Cd) dan nikel (Ni) semasa pemendakan MAP. Tiga jenis sisa tulang telah diuji bagi sumber P berkos rendah, iaitu abu sisa tulang ikan, ayam dan lembu. Abu tulang ikan mempunyai kandungan P tertinggi (17% berat). Pengekstrakan P oleh larut lesapan asid telah dioptimumkan dengan Kaedah Permukaan Tindak Balas (RSM) dan hasil kajian menunjukkan bahawa penggunaan 2M H_2SO_4 dan 1.25 kg H_2SO_4/kg abu menghasilkan pengestrakan 95% P. Larutan P yang diekstrak (150 g-P/L) telah berjaya digunakan dalam pemendakan MAP. Perolehan NH_4-N dalam sintetik LL telah dioptimumkan menggunakan RSM. Perolehan maksimum NH_4-N (90%) dicapai pada pH 8.5, Mg:N = 1.25, K:N = 0.1 dan $G = 95\ s^{-1}$. Kesan bahan organik terhadap perolehan MAP ditentukan dengan menggunakan LL sintetik dan sebenar (dituras dan tidak dituras). Asid propionik, butirik dan asetik dirumuskan untuk kandungan organik dalam LL sintetik, yakni kesan yang tidak ketara didapati dengan penyingkiran kecil jumlah karbon organik (TOC) (6.30-13.96%). Bagi LL sebenar, masing-masing perolehan NH_4-N sekitar 93%, 71% dan 28% telah dicapai dengan menggunakan $MgCl_2+Na_2HPO_4$, larutan MgO+P dan $MgO+Na_2HPO_4$. Juga didapati Cd dan Ni mendak bersama dengan MAP, membentuk analog struvit yang boleh menjejaskan keaslian MAP. Kemampanan perolehan NH_4-N perlu dipertingkatkan lagi supaya lebih berkesan untuk penggunaan rawatan LL pada skala yang lebih besar.

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LIST OF ABBREVIATIONS

AAS	-	Atomic absorption spectrometry
ANOVA	-	Analysis of variance
BOD	-	Biological oxygen demand
COD	-	Chemical oxygen demand
EBPR	-	Enhanced Biological Phosphorus Removal
Eqn.	-	Equation
FBA	-	Fish bone ash
HRT	-	Hydraulic retention time
ICP-OES	-	Inductively coupled plasma-optical emission spectroscopy
LL	-	Landfill leachate
MAP	-	Magnesium ammonium phosphate (Struvite)
MPP	-	Magnesium potassium phosphate (Struvite-K)
SEM-EDX	-	Scanning electron microscopy-Energy dispersive X ray
SS	-	Suspended solids
TC	-	Total carbon
TOC	-	Total organic carbon
TSS	-	Total suspended solids
WWTP	-	Wastewater Treatment Plant

LIST OF SYMBOLS

Al	-	Aluminum
As	-	Arsenic
°C	-	Celsius
Ca	-	Calcium
$CaHPO_4.2H_2O$	-	Dicalcium phosphate
$Ca(H_2PO_4)_2.H_2O$	-	Monocalcium phosphate
Cd	-	Cadmium
CH_3COOH	-	Acetic acid
Cl	-	Chloride
Cr	-	Chromium
Cu	-	Copper
G	-	Mixing intensity
h	-	Hour
H_2SO_4	-	Sulfuric acid
H_3PO_4	-	Phosphoric acid
HCl	-	Hydrochloric acid
K	-	Potassium
M	-	Mole
Mg	-	Magnesium
$MgCl_2.6H_2O$	-	Magnesium chloride hexahydrate
MgO	-	Magnesium oxide

$Mg(OH)_2$	-	Magnesium hydroxide (Brucite)
N	-	Nitrogen
$Na_2HPO_4.2H_2O$	-	Disodium phosphate dihydrate
NaClO	-	Sodium hypochlorite
NaOH	-	Sodium hydroxide
NH_4-N	-	Ammonium nitrogen
Ni	-	Nickel
P	-	Phosphorus
PO_4	-	Phosphate
t_d	-	Mixing duration
Zn	-	Zinc

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CHAPTER 1

INTRODUCTION

1.1 Overview

Landfilling is a common method applied for solid waste disposal, especially in low- and middle-income countries. It is recognized as an important option both now and in the near future. In Malaysia, 95% of the collected solid wastes are landfilled, with roughly 5% being recycled (Johari et al., 2014). Such situation has several consequences on the environment around the landfills, as the huge amounts of wastes produce different by-products, such as biogas and leachate.

Landfill leachate (LL) is the liquid produced as a result of different chemical and biochemical reactions that took place when water percolates through the disposed landfill waste components. Landfill leachate is a high strength waste stream that contains high concentrations of organics, suspended solids (SS) and nitrogen (N), namely ammonium nitrogen (NH_4-N) (Ismail and Manaf, 2013). High-ammonium from LL has been known to cause eutrophication to surface water bodies and result in pollution to groundwater and aquaculture (Taha et al., 2011; Marañón et al., 2006).

Biological treatment methods (aerobic or anaerobic) have the capability to reduce organic loads from wastewater. However, they are less efficient when applied to LL (Zhang et al., 2009a), especially when it is in the methanogenic (mature) phase (Di Iaconi et al., 2010). The reason is that mature LL holds large amounts of recalcitrant organics and very high concentrations of NH_4-N that has toxic inhibition to microorganisms responsible for the biological degradation. Moreover, the ratio of biological oxygen demand/chemical oxygen demand (BOD_5/COD) in this phase of LL is frequently much lower than required for efficient biological processes (Siciliano et al., 2013), making the application of such conventional methods more expensive and difficult.

Several techniques have been applied for LL treatment such as ammonia stripping (Leite et al., 2013), ion exchange (Boyer et al., 2011) and electrochemical oxidation (Bashir et al., 2009). The cost of ammonia stripping method is considered high, as huge stripping towers have to be built, as well as large amounts of sulfuric acid (H_2SO_4) is needed to recover ammonia (NH_3) in the form of ammonium sulphate ($(NH_4)_2SO_4$) (See section 2.3). The main constraint that hinders the development of an effective NH_4-N treatment by ion exchange method is the high cost of resins that are needed to be changed frequently, while the major problem in achieving large-scale application of electro-oxidation is the high electricity consumption together with the high cost of electrodes.

The process of chemical precipitation of NH_4-N, forming magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4.6H_2O$, MAP), known as struvite, has been thoroughly investigated for different types of wastewater (Huang et al., 2016c; Chen et al., 2013; Ryu and Lee, 2010; Warmadewanthi and Liu, 2009; Liu et al., 2008), which showed high efficacy in nutrients' recovery. The process of NH_4-N recovery by struvite precipitation has unique benefits; it has the ability to treat high concentrations of NH_4-N, as well as recovering it into valuable material, which is not available in other nitrogen treatment methods. In addition, struvite has significant benefits for the agronomic field; it is an effective fertilizer as its nutrients are released slowly, causing no adverse effects on plants roots (Rahman et al., 2014). Moreover, MAP precipitation technology had shown an effectiveness higher than many other methods such as the biological treatment methods (Akkaya et al., 2010), ammonia stripping (Hidalgo et al., 2016) and fenton oxidation (Kochany and Lipczynska-Kochany, 2009).

However, LL is usually poor in magnesium (Mg) and phosphorus (P), which makes struvite precipitation costly, due to the required addition of Mg and P. Therefore, using low-cost sources of Mg and P could significantly reduce the operational costs of the process (Liu et al., 2013a; Siciliano et al., 2013; Borojovich et al., 2010; Di Iaconi et al., 2010). Fundamentally, struvite precipitation is influenced by several factors, mainly pH, molar ratios of Mg:N and P:N, initial NH_4-N concentration and mixing intensity (*G*). The presence of foreign ions, mainly calcium (Ca) and potassium (K), could lower the efficiency of NH_4-N. Calcium ions has the ability to react with phosphate, while the presence of K could result with the formation of magnesium potassium phosphate hexahydrate ($MgKPO_4.6H_2O$), which competes with MAP. Besides, recovery of pure MAP could be impeded by the presence of organic matter in the stream (Gunay et al., 2008b).

During the process of NH_4-N recovery from LL, heavy metals may contaminate the produced struvite. Several studies illustrated that heavy metals could be incorporated into struvite's crystal network, or sorbed onto its surface (Ronteltap et al., 2007). Thereafter, if struvite would be used as a fertilizer, the incorporated heavy metals might cause hazardous impacts on humans and plants. Different heavy metals, like Ni & Cd, were found in quite high concentrations in leachates of different landfills in Malaysia (Yusof et al., 2009) and Palestine (Alslaibi et al., 2011). However, their sorption mechanisms during MAP precipitation are still undefined.

1.2 Problem statement

Landfill leachate is a high-strength waste stream, containing high concentration of NH_4-N that is difficult to be treated by traditional biological methods. Disposing LL without a proper treatment causes significant pollution for surface and groundwater, consequently affecting human health and aquatic life.

Struvite precipitation is a promising solution that has been investigated for NH_4-N and P recovery. However, the high cost of raw Mg and P reagents is still the main obstacle in sustainable application of struvite precipitation. Whilst most of researches tended to investigate alternative sources of Mg (Ye et al., 2011; Gunay et al., 2008b; Chimenos et al., 2003), little efforts have been carried out to investigate the alternative low-cost sources of P (Siciliano et al., 2013) despite the fact that P is more expensive and rare as compared to Mg (Di Iaconi et al., 2010).

As LL has a complex nature, there are many elements that could have negative effects on MAP precipitation, thus inhibiting NH_4-N removal. The presence of Potassium (K^+) has been proven to affect the purity of MAP by forming a different struvite analogue. In the same context, high concentration of K^+ has been found in different LLs in Malaysia. However, the interaction effect of K with pH, Mg:N and *G* has not been determined before.

Organic matter can cause mutual effects with NH_4-N, which may affect NH_4-N removal and struvite purity as well. In particular, propionic, butyric and acetic acids are the main carboxylic acids that formulate the organic matter of LL. However, their potential influence on NH_4-N recovery has not been reported in the literature. In addition, the efficiency of applying the alternative P (P extraction) has to be determined.

High concentrations of Cd and Ni have been found in LL in some countries like Malaysia and Palestine. These heavy metals could drastically influence the purity of struvite as a fertilizer. A comprehensive explanation of Cd and Ni effect and behaviour during MAP precipitation is still lacking, which should be discussed in detail.

1.3 Objectives

The main goal of this study is to develop a sustainable approach for NH_4-N recovery from municipal LL by means of struvite precipitation method. The following objectives are proposed to be achieved:

1. To choose the best type of waste bone ash to be used as a low-cost source of phosphorus required for struvite precipitation.

2. To optimize NH_4-N recovery and struvite purity in terms of K^+, pH, Mg:N molar ratio and *G*.

3. To investigate the potential effect of organic matter in synthetic LL on NH_4-N recovery, as well as the efficiency of P extraction for NH_4-N recovery from actual LL.

4. To study the effect and sorption mechanisms of Cd and Ni during struvite precipitation.

1.4 Scope of study

This study investigates the recovery of NH_4-N from LL via struvite crystallization technology. Three types of waste bones, produced from fish, chicken and cow were characterized to choose the best alternative P source among them to apply it in MAP formation. Consequently, P extraction from the best wasted bone ash (fish wasted bone ash) was optimized by Response Surface Methodology (RSM). The interaction effects of pH, Mg:N and K:N molar ratios and *G* on NH_4-N removal from synthetic LL were also optimized using RSM. The influences of three organic acids (propionic, butyric and acetic acids) on struvite recovery was also studied. The efficiency of P extraction in MAP recovery from actual LL was determined. Furthermore, the effect and sorption mechanisms of Cd and Ni during struvite precipitation process was defined.

1.5 Limitation of study

This study discussed some aspects related to NH_4-N recovery from LL by MAP precipitation. However, some other aspects could not be covered such as:

1. The alternative source of Mg, as the main purpose was to discover a new alternative P source, and study its efficiency in MAP precipitation.
2. Not all influencing factors that affect MAP recovery were investigated. Instead, based on the literature, the most influential factors were considered.
3. A combination of only three organic acids was applied to represent the organic content in the synthetic leachate. This was because the sole parameter that measured the organic content was TOC, as the other indicators, according to literature, are either does not represent the organic carbon alone such as COD, or not affected by the chemical precipitation process such as BOD.

1.6 Significance of study

MAP precipitation is a promissing approach to remove and recover NH_4-N from LL. On the whole, this study will contribute to the environment protection, through the attainment of sustainable removal of NH_4-N from LL, and production of valuable materials.

In particular, extracting P from wasted bones ash and using it in MAP recovery has several benefits:

1. Decreasing the consumption of natural sources of P (phosphate rocks), which are threatened to be depleted in the next coming 50 years.

2. Contributing to minimize organic wastes disposal and recover the contained nutrients.

Additionally, considering the influential factors and the different levels of LL pollution, determining the optimum condition of struvite precipitation will explain the potential interferences that may inhibit the effecient recovery of NH_4-N. Furthermore, this can be considered as a milestone for large-scale applications of struvite recovery. Moreover, focusing on heavy metals and their impact on struvite purity will benefit in estimating the level of potential contamination with heavy metals, as well as assessing the feasibility of using struvite, recovered from LL, as a fertilizer.

REFERENCES

Abbona, F., Angela-Franchini, M., Croni Bono, C. and Lundager Madsen, H.E. (1994). Effect of ammonia excess on the crystal habit of $NiNH_4PO_4 \cdot 6H_2O$ (Ni-struvite). *Journal of Crystal Growth*. 143, 256-260.

Acelas, N.Y., Flórez, E. and López, D. (2014). Phosphorus recovery through struvite precipitation from wastewater: effect of the competitive ions. *Desalination and Water Treatment*. 54, 2468-2479.

Akgul, D., Aktan, C.K., Yapsakli, K. and Mertoglu, B. (2013). Treatment of landfill leachate using UASB-MBR-SHARON–Anammox configuration. *Biodegradation*. 24, 399-412.

Akkaya, E., Demir, A., Karadag, D., Varank, G., Bilgili, M.S. and Ozkaya, B. (2010). Post-treatment of anaerobically treated medium-age landfill leachate. *Environmental Progress & Sustainable Energy*. 29, 78-84.

Alslaibi, T.M., Mogheir, Y.K. and Afifi, S. (2011). Assessment of Groundwater Quality Due to Municipal Solid Waste Landfills Leachate. *Environmental Science & Technology*. 4, 419-436.

Anglada, A., Urtiaga, A., Ortiz, I., Mantzavinos, D. and Diamadopoulos, E. (2011). Boron-doped diamond anodic treatment of landfill leachate: Evaluation of operating variables and formation of oxidation by-products. *Water Research*. 45, 828-838.

APHA (2005). *Standard Methods for the Examination of Water and Wastewater,* Washington, DC, American Public Health Association, American Water Works Association, and Water Environment Federation.

Barnes, D., Li, X. and Chen, J. (2007). Determination of suitable pretreatment method for old-intermediate landfill leachate. *Environmental Technology*. 28, 195 - 203.

Bashir, M.J.K., Aziz, H.A., Yusoff, M.S. and Adlan, M.N. (2010). Application of response surface methodology (RSM) for optimization of ammoniacal nitrogen removal from semi-aerobic landfill leachate using ion exchange resin. *Desalination*. 254, 154-161.

Bashir, M.J.K., Isa, M.H., Kutty, S.R.M., Awang, Z.B., Aziz, H.A., Mohajeri, S. and Farooqi, I.H. (2009). Landfill leachate treatment by electrochemical oxidation. *Waste Management*. 29, 2534-2541.

Bhuiyan, M.I.H., Mavinic, D.S. and Koch, F.A. (2008). Thermal decomposition of struvite and its phase transition. *Chemosphere*. 70, 1347-1356.

Borgerding, J. (1972). Phosphate deposits in digestion systems. *Journal of the Water Pollution Control Federation*. 44, 813–819.

Borojovich, E.J.C., Münster, M., Rafailov, G. and Porat, Z.e. (2010). Precipitation of Ammonium from Concentrated Industrial Wastes as Struvite: A Search for the Optimal Reagents. *Water Environment Research*. 82, 586-591.

Boyer, T.H., Graf, K.C., Comstock, S.E.H. and Townsend, T.G. (2011). Magnetic ion exchange treatment of stabilized landfill leachate. *Chemosphere*. 83, 1220-1227.

Capdevielle, A., Sýkorová, E., Biscans, B., Béline, F. and Daumer, M.L. (2013). Optimization of struvite precipitation in synthetic biologically treated swine wastewater—Determination of the optimal process parameters. *Journal of Hazardous Materials*. 244–245, 357-369.

Chen, Y., Liu, C., Nie, J., Luo, X. and Wang, D. (2013). Chemical precipitation and biosorption treating landfill leachate to remove ammonium-nitrogen. *Clean Technologies and Environmental Policy*. 15, 395-399.

Chimenos, J.M., Fernández, A.I., Villalba, G., Segarra, M., Urruticoechea, A., Artaza, B. and Espiell, F. (2003). Removal of ammonium and phosphates from wastewater resulting from the process of cochineal extraction using MgO-containing by-product. *Water Research*. 37, 1601 - 1607.

Cohen, Y. (2009). Phosphorus dissolution from ash of incinerated sewage sludge and animal carcasses using sulphuric acid. *Environmental Technology*. 30, 1215-1226.

Cornwell, D.A. and Bishop, M.M. (1983). Determining velocity gradients in laboratory and field scale systems. *Journal of the American Water Works Association*. 75, 470-475.

Coutand, M., Cyr, M., Deydier, E., Guilet, R. and Clastres, P. (2008). Characteristics of industrial and laboratory meat and bone meal ashes and their potential applications. *Journal of Hazardous Materials*. 150, 522-532.

Daniel, H., Perinaz, B. 2012. What a waste: a global review of solid waste management. *Urban development series.* Washington D.C.: World Bank.

Degryse, F., Baird, R., da Silva, R.C. and McLaughlin, M.J. (2016). Dissolution rate and agronomic effectiveness of struvite fertilizers – effect of soil pH, granulation and base excess. *Plant and Soil*. 1-14.

Desmidt, E., Ghyselbrecht, K., Monballiu, A., Verstraete, W. and Meesschaert, B.D. (2012). Evaluation and thermodynamic calculation of ureolytic magnesium ammonium phosphate precipitation from UASB effluent at pilot scale. *Water Science & Technology*. 65, 1954-1962.

Di Iaconi, C., Pagano, M., Ramadori, R. and Lopez, A. (2010). Nitrogen recovery from a stabilized municipal landfill leachate. *Bioresource Technology*. 101, 1732-1736.

Driver, J., Lijmbach, D. and Steen, I. (1999). Why recover phosphorus for recycling, and how? *Environmental Technology*. 20, 651-662.

Escudero, A., Blanco, F., Lacalle, A. and Pinto, M. (2015). Struvite precipitation for ammonium removal from anaerobically treated effluents. *Journal of Environmental Chemical Engineering*. 3, 413-419.

Etter, B., Tilley, E., Khadka, R. and Udert, K.M. (2011). Low-cost struvite production using source-separated urine in Nepal. *Water Research*. 45, 852-862.

Foo, K.Y., Lee, L.K. and Hameed, B.H. (2013). Batch adsorption of semi-aerobic landfill leachate by granular activated carbon prepared by microwave heating. *Chemical Engineering Journal*. 222, 259-264.

Frascari, D., Bronzini, F., Giordano, G., Tedioli, G. and Nocentini, M. (2004). Long-term characterization, lagoon treatment and migration potential of landfill leachate: a case study in an active Italian landfill. *Chemosphere*. 54, 335-343.

Guadie, A., Xia, S., Jiang, W., Zhou, L., Zhang, Z., Hermanowicz, S.W., Xu, X. and Shen, S. (2014). Enhanced struvite recovery from wastewater using a novel cone-inserted fluidized bed reactor. *Journal of Environmental Sciences*. 26, 765-774.

Gunay, A., Karadag, D., Tosun, I. and Öztürk, M. (2008a). Combining Anerobic Degradation and Chemical Precipitation for the Treatment of High Strength, Strong Nitrogenous Landfill Leachate. *CLEAN – Soil, Air, Water*. 36, 887-892.

Gunay, A., Karadag, D., Tosun, I. and Öztürk, M. (2008b). Use of magnesit as a magnesium source for ammonium removal from leachate. *Journal of Hazardous Materials*. 156, 619-623.

Hao, X., Wang, C., van Loosdrecht, M.C.M. and Hu, Y. (2013). Looking Beyond Struvite for P-Recovery. *Environmental Science & Technology*. 47, 4965-4966.

Hao, X.D., Wang, C.C., Lan, L. and van Loosdrecht, M.C.M. (2008). Struvite formation, analytical methods and effects of pH and Ca^{2+}. *Water Science & Technology*. 58, 1687-1692.

He, S., Zhang, Y., Yang, M., Du, W. and Harada, H. (2007). Repeated use of MAP decomposition residues for the removal of high ammonium concentration from landfill leachate. *Chemosphere*. 66, 2233-2238.

Hidalgo, D., Corona, F., Martín-Marroquín, J.M., del Álamo, J. and Aguado, A. (2016). Resource recovery from anaerobic digestate: struvite crystallisation versus ammonia stripping. *Desalination and Water Treatment*. 57, 2626-2632.

Hilt, K., Harrison, J., Bowers, K., Stevens, R., Bary, A. and Harrison, K. (2016). Agronomic Response of Crops Fertilized with Struvite Derived from Dairy Manure. *Water, Air, & Soil Pollution*. 227, 388-401.

Huang, H., Huang, L., Zhang, Q., Jiang, Y. and Ding, L. (2015). Chlorination decomposition of struvite and recycling of its product for the removal of ammonium-nitrogen from landfill leachate. *Chemosphere*. 136, 289-296.

Huang, H., Liu, J., Wang, S., Jiang, Y., Xiao, D., Ding, L. and Gao, F. (2016a). Nutrients removal from swine wastewater by struvite precipitation recycling technology with the use of Mg3(PO4)2 as active component. *Ecological Engineering*. 92, 111-118.

Huang, H., Liu, J., Xu, C. and Gao, F. (2016b). Recycling struvite pyrolysate obtained at negative pressure for ammonia nitrogen removal from landfill leachate. *Chemical Engineering Journal*. 284, 1204-1211.

Huang, H., Mavinic, D.S., Lo, K.V. and Koch, F.A. (2006). Production and basic morphology of struvite crystals from a pilot-scale crystallization process. *Environmental Technology*. 27, 233-245.

Huang, H., Song, Q., Zhao, X., Chen, Y. and Xu, C. (2012). Reduction in the cost for ammonia removal by struvite precipitation technology. *Energy Education Science and Technology Part A: Energy Science and Research*. 29, 289-298.

Huang, H., Xiao, D., Zhang, Q. and Ding, L. (2014). Removal of ammonia from landfill leachate by struvite precipitation with the use of low-cost phosphate and magnesium sources. *Journal of Environmental Management*. 145, 191-198.

Huang, H., Xiao, X., Yang, L. and Yan, B. (2010). Recovery of nitrogen from saponification wastewater by struvite precipitation. *Water Science and Technology*. 61, 2741-2748.

Huang, H., Xu, C. and Zhang, W. (2011a). Removal of nutrients from piggery wastewater using struvite precipitation and pyrogenation technology. *Bioresource Technology*. 102, 2523-2528.

Huang, H., Zhang, P., Zhang, Z., Liu, J., Xiao, J. and Gao, F. (2016c). Simultaneous removal of ammonia nitrogen and recovery of phosphate from swine wastewater by struvite electrochemical precipitation and recycling technology. *Journal of Cleaner Production*. 127, 302-310.

Huang, H.M., Xiao, X.M., Yang, L.P. and Yan, B. (2011b). Removal of ammonium from rare-earth wastewater using natural brucite as a magnesium source of struvite precipitation. *Water Science and Technology*. 63, 468-474.

Hutnik, N., Kozik, A., Mazienczuk, A., Piotrowski, K., Wierzbowska, B. and Matynia, A. (2013). Phosphates (V) recovery from phosphorus mineral fertilizers industry wastewater by continuous struvite reaction crystallization process. *Water Research*. 47, 3635-3643.

Ismail, S.N.S. and Manaf, L.A. (2013). The challenge of future landfill: A case study of Malaysia. *Journal of Toxicology and Environmental Health Sciences*. 5, 86-96.

Jaafarzadeh, N., Jorfi, S., Kalantary, R.R., Hashempour, Y. and Soltani, R.D. (2010). Evaluation of biological landfill leachate treatment incorporating struvite precipitation and powdered activated carbon addition. *Waste Manag Res*. 28, 759-766.

Jingsheng, C., Tao, Y. and Ongley, E. (2006). Influence of High Levels of Total Suspended Solids on Measurement of Cod and Bod in the Yellow River, China. *Environmental Monitoring and Assessment*. 116, 321-334.

Johari, A., Alkali, H., Hashim, H., I. Ahmed, S. and Mat, R. (2014). Municipal Solid Waste Management and Potential Revenue from Recycling in Malaysia. *Modern Applied Science*. 8, 37-49.

Kabdaşli, I., Şafak, A. and Tünay, O. (2008). Bench-scale evaluation of treatment schemes incorporating struvite precipitation for young landfill leachate. *Waste Management*. 28, 2386-2392.

Kabdaşli, I., Tünay, O., Öztürk, I., Yilmaz, Z. and Arikan, O. (2000). Ammonia removal from young landfill leachate by magnesium ammonium phosphate precipitation and air stripping. *Water Science and Technology*. 41, 237-240.

Kamaruddin, M., Yusoff, M., Aziz, H. and Basri, N. (2013). Removal of COD, ammoniacal nitrogen and colour from stabilized landfill leachate by anaerobic organism. *Applied Water Science*. 3, 359-366.

Kim, D., Kim, J., Ryu, H.D. and Lee, S.I. (2009). Effect of mixing on spontaneous struvite precipitation from semiconductor wastewater. *Bioresource Technology*. 100, 74-78.

Kim, D., Ryu, H.D., Kim, M.S., Kim, J. and Lee, S.I. (2007). Enhancing struvite precipitation potential for ammonia nitrogen removal in municipal landfill leachate. *Journal of Hazardous Materials*. 146, 81-85.

Kochany, J. and Lipczynska-Kochany, E. (2009). Utilization of landfill leachate parameters for pretreatment by Fenton reaction and struvite precipitation--a comparative study. *Journal of Hazardous Materials*. 166, 248-254.

Kumar, R. and Pal, P. (2013). Turning hazardous waste into value-added products: production and characterization of struvite from ammoniacal waste with new approaches. *Journal of Cleaner Production*. 43, 59-70.

Lahav, O., Telzhensky, M., Zewuhn, A., Gendel, Y., Gerth, J., Calmano, W. and Birnhack, L. (2013). Struvite recovery from municipal-wastewater sludge centrifuge supernatant using seawater NF concentrate as a cheap Mg(II) source. *Separation and Purification Technology*. 108, 103-110.

Le Corre, K.S., Valsami-Jones, E., Hobbs, P. and Parsons, S.A. (2009). Phosphorus Recovery from Wastewater by Struvite Crystallization: A Review. *Critical Reviews in Environmental Science and Technology*. 39, 433-477.

Lee, J.E., Rahman, M.M. and Ra, C.S. (2009). Dose effects of Mg and PO4 sources on the composting of swine manure. *Journal of Hazardous Materials*. 169, 801-807.

Lee, S.-h., Kumar, R. and Jeon, B.-H. (2016). Struvite precipitation under changing ionic conditions in synthetic wastewater: Experiment and modeling. *Journal of Colloid and Interface Science*. 474, 93-102.

Lee, S.H., Yoo, B.H., Kim, S.K., Lim, S.J., Kim, J.Y. and Kim, T.H. (2013). Enhancement of struvite purity by re-dissolution of calcium ions in synthetic wastewaters. *Journal of Hazardous Materials*. 261, 29-37.

Lee, S.I., Weon, S.Y., Lee, C.W. and Koopman, B. (2003). Removal of nitrogen and phosphate from wastewater by addition of bittern. *Chemosphere*. 51, 265-271.

Lehmann, E.C. (2007). *Landfill Research Focus,* Nova Science Publishers.

Leite, V.D., Prasad, S., Lopes, W.S., de Sousa, J.T. and Barros, A.J.M. (2013). Study on ammonia stripping process of leachate from the packed towers. *Journal of Urban and Environmental Engineering*. 7, 215-222.

Lew, B., Phalah, S., Sheindorf, C., Kummel, M., Rebhun, M. and Lahav, O. (2010). Favorable Operating Conditions for Obtaining High-Value Struvite Product from Sludge Dewatering Filtrate. *Environmental Engineering Science*. 27, 733-741.

Li, W., Ding, X., Liu, M., Guo, Y. and Liu, L. (2012). Optimization of process parameters for mature landfill leachate pretreatment using MAP precipitation. *Frontiers of Environmental Science & Engineering*. 6, 892-900.

Li, X.Z. and Zhao, Q.L. (2002). MAP Precipitation from Landfill Leachate and Seawater Bittern Waste. *Environmental Technology*. 23, 989-1000.

Li, X.Z., Zhao, Q.L. and Hao, X.D. (1999). Ammonium removal from landfill leachate by chemical precipitation. *Waste Management*. 19, 409-415.

Liu, B., Giannis, A., Zhang, J., Chang, V.W. and Wang, J.Y. (2013a). Characterization of induced struvite formation from source-separated urine using seawater and brine as magnesium sources. *Chemosphere*. 93, 2738-2747.

Liu, Y., Kumar, S., Kwag, J., Kim, J., Kim, J. and Ra, C. (2011a). Recycle of electrolytically dissolved struvite as an alternative to enhance phosphate and nitrogen recovery from swine wastewater. *Journal of Hazardous Materials*. 195, 175-181.

Liu, Y., Kumar, S., Kwag, J.H. and Ra, C. (2013b). Magnesium ammonium phosphate formation, recovery and its application as valuable resources: a review. *Journal of Chemical Technology & Biotechnology*. 88, 181-189.

Liu, Y., Kwag, J.H., Kim, J.H. and Ra, C. (2011b). Recovery of nitrogen and phosphorus by struvite crystallization from swine wastewater. *Desalination*. 277, 364-369.

Liu, Z., Zhao, Q., Wang, K., Lee, D., Qiu, W. and Wang, J. (2008). Urea hydrolysis and recovery of nitrogen and phosphorous as MAP from stale human urine. *Journal of Environmental Sciences*. 20, 1018-1024.

Long, R.B. (1995). *Separation Processes in Waste Minimization*, Taylor & Francis.

Lu, X., Shih, K., Li, X.-y., Liu, G., Zeng, E.Y. and Wang, F. (2016). Accuracy and application of quantitative X-ray diffraction on the precipitation of struvite product. *Water Research*. 90, 9-14.

Ma, N. and Rouff, A.A. (2012). Influence of pH and Oxidation State on the Interaction of Arsenic with Struvite During Mineral Formation. *Environmental Science & Technology*. 46, 8791-8798.

Marañón, E., Ulmanu, M., Fernández, Y., Anger, I. and Castrillón, L. (2006). Removal of ammonium from aqueous solutions with volcanic tuff. *Journal of Hazardous Materials*. 137, 1402-1409.

Matynia, A., Wierzbowska, B., Hutnik, N., Mazienczuk, A., Kozik, A. and Piotrowski, K. (2013). Separation of Struvite from Mineral Fertilizer Industry Wastewater. *Procedia Environmental Sciences*. 18, 766-775.

Mehta, C.M. and Batstone, D.J. (2013). Nucleation and growth kinetics of struvite crystallization. *Water Research*. 47, 2890-2900.

Morling, S., Kth, Skolan för arkitektur och, s. and Mark- och, v. (2010). Nitrogen removal and heavy metals in leachate treatment using SBR technology. *Journal of Hazardous Materials*. 174, 679-686.

Münch, E.V. and Barr, K. (2001). Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams. *Water Research*. 35, 151-159.

Muryanto, S. and Bayuseno, A.P. (2014). Influence of Cu^{2+} and Zn^{2+} as additives on crystallization kinetics and morphology of struvite. *Powder Technology*. 253, 602-607.

Nurisepehr, M., Jorfi, S., Rezaei Kalantary, R., Akbari, H., Soltani, R.D. and Samaei, M. (2012). Sequencing treatment of landfill leachate using ammonia stripping, Fenton oxidation and biological treatment. *Waste Management & Research*. 30, 883-887.

Oliva, J., De Pablo, J., Cortina, J.-L., Cama, J. and Ayora, C. (2011). Removal of cadmium, copper, nickel, cobalt and mercury from water by Apatite II™: Column experiments. *Journal of Hazardous Materials*. 194, 312-323.

Öztürk, I., Altinbas, M., Koyuncu, I., Arikan, O. and Gomec-Yangin, C. (2003). Advanced physico-chemical treatment experiences on young municipal landfill leachates. *Waste Management*. 23, 441-446.

Pal, P. and Kumar, R. (2014). Treatment of Coke Wastewater: A Critical Review for Developing Sustainable Management Strategies. *Separation & Purification Reviews*. 43, 89-123.

Pastor, L., Mangin, D., Barat, R. and Seco, A. (2008). A pilot-scale study of struvite precipitation in a stirred tank reactor: Conditions influencing the process. *Bioresource Technology*. 99, 6285-6291.

Rahman, M.M., Liu, Y., Kwag, J.H. and Ra, C. (2011). Recovery of struvite from animal wastewater and its nutrient leaching loss in soil. *Journal of Hazardous Materials*. 186, 2026-2030.

Rahman, M.M., Salleh, M.A.M., Rashid, U., Ahsan, A., Hossain, M.M. and Ra, C.S. (2014). Production of slow release crystal fertilizer from wastewaters through struvite crystallization – A review. *Arabian Journal of Chemistry*. 7, 139-155.

Rawn, A., Perry Banta, A. and Pomeroy, R. (1937). Multiple-stage sewage sludge digestion. *American Society of Civil Engineers*. 2116, 93-132.

Ronteltap, M., Maurer, M. and Gujer, W. (2007). The behaviour of pharmaceuticals and heavy metals during struvite precipitation in urine. *Water Research*. 41, 1859-1868.

Rouff, A. (2012a). The use of TG/DSC–FT-IR to assess the effect of Cr sorption on struvite stability and composition. *Journal of Thermal Analysis and Calorimetry*. 110, 1217-1223.

Rouff, A.A. (2012b). Sorption of Chromium with Struvite During Phosphorus Recovery. *Environmental Science & Technology*. 46, 12493-12501.

Rowe, R.K., VanGulck, J.F. and Millward, S.C. (2002). Biologically induced clogging of a granular medium permeated with synthetic leachate. *Journal of Environmental Engineering and Science*. 1, 135-156.

Ryu, H.D., Kim, D. and Lee, S.I. (2008). Application of struvite precipitation in treating ammonium nitrogen from semiconductor wastewater. *Journal of Hazardous Materials*. 156, 163-169.

Ryu, H.D. and Lee, S.I. (2010). Application of struvite precipitation as a pretreatment in treating swine wastewater. *Process Biochemistry*. 45, 563-572.

Ryu, H.D., Lim, C.S., Kang, M.K. and Lee, S.I. (2012). Evaluation of struvite obtained from semiconductor wastewater as a fertilizer in cultivating Chinese cabbage. *Journal of Hazardous Materials*. 221–222, 248-255.

Sadiq, M. (1992). *Toxic Metal Chemistry in Marine Environments*, Taylor & Francis.

Schoumans, O., Bouraoui, F., Kabbe, C., Oenema, O. and van Dijk, K. (2015). Phosphorus management in Europe in a changing world. *Ambio*. 44, 180-192.

Schuiling, R.D. and Andrade, A. (1999). Recovery of Struvite from Calf Manure. *Environmental Technology*. 20, 765-768.

Siciliano, A. and De Rosa, S. (2014). Recovery of ammonia in digestates of calf manure through a struvite precipitation process using unconventional reagents. *Environmental Technology*. 35, 841-850.

Siciliano, A., Ruggiero, C. and De Rosa, S. (2013). A new integrated treatment for the reduction of organic and nitrogen loads in methanogenic landfill leachates. *Process Safety and Environmental Protection*. 91, 311-320.

Siciliano, A., Stillitano, M., Limonti, C. and Marchio, F. (2016). Ammonium Removal from Landfill Leachate by Means of Multiple Recycling of Struvite Residues Obtained through Acid Decomposition. *Applied Sciences*. 6, 375-392.

Sin, T.J., Chen, G.K. and Hwang, G.H. (Year). Challenges in Selecting a Sustainable Landfill Site in Malaysia. ICon CEES 2015, 2016. MATEC Web of Conferences, 05021.

Song, Y., Dai, Y., Hu, Q., Yu, X. and Qian, F. (2014). Effects of three kinds of organic acids on phosphorus recovery by magnesium ammonium phosphate (MAP) crystallization from synthetic swine wastewater. *Chemosphere*. 101, 41-48.

Song, Y.H., Qiu, G.L., Yuan, P., Cui, X.Y., Peng, J.F., Zeng, P., Duan, L., Xiang, L.C. and Qian, F. (2011). Nutrients removal and recovery from anaerobically digested swine wastewater by struvite crystallization without chemical additions. *Journal of Hazardous Materials*. 190, 140-149.

Suguna, K., Thenmozhi, M. and Sekar, C. (2012). Growth, spectral, structural and mechanical properties of struvite crystal grown in presence of sodium fluoride. *Bulletin of Materials Science*. 35, 701-706.

Suzuki, K., Tanaka, Y., Kuroda, K., Hanajima, D., Fukumoto, Y., Yasuda, T. and Waki, M. (2007). Removal and recovery of phosphorous from swine wastewater by demonstration crystallization reactor and struvite accumulation device. *Bioresource Technology*. 98, 1573-1578.

Taha, M.R., Yaacob, W.Z.W., Samsudin, A.R. and Yaakob, J. (2011). Groundwater quality at two landfill sites in Selangor, Malaysia. *Bulletin of the Geological Society of Malaysia*. 13-18.

Türker, M. and Çelen, I. (2007). Removal of ammonia as struvite from anaerobic digester effluents and recycling of magnesium and phosphate. *Bioresource Technology*. 98, 1529-1534.

Uludag-Demirer, S., Demirer, G.N. and Chen, S. (2005). Ammonia removal from anaerobically digested dairy manure by struvite precipitation. *Process Biochemistry*. 40, 3667-3674.

Usyal, A. and Kuru, B. (2013). Examination of nutrient removal from anaerobic effluent of the dairy processing industry by struvite precipitation using the response surface methodology. *Fresenius Environmental Bulletin*. 22, 1380-1387.

Uysal, A., Demir, S., Sayilgan, E., Eraslan, F. and Kucukyumuk, Z. (2014). Optimization of struvite fertilizer formation from baker's yeast wastewater: growth and nutrition of maize and tomato plants. *Environmental Science and Pollution Research*. 21, 3264–3274.

Uysal, A., Yilmazel, Y.D. and Demirer, G.N. (2010). The determination of fertilizer quality of the formed struvite from effluent of a sewage sludge anaerobic digester. *Journal of Hazardous Materials*. 181, 248-254.

Wang, C.C., Hao, X.D., Guo, G.S. and van Loosdrecht, M.C.M. (2010). Formation of pure struvite at neutral pH by electrochemical deposition. *Chemical Engineering Journal*. 159, 280-283.

Wang, H., Cheng, G.W., Song, X.W., Xu, Z.H., Meng, J.J. and Dong, C.Q. (2012). Pretreatment of High Strength Ammonia Removal from Rare-Earth Wastewater by Magnesium Ammonium Phosphate (MAP) Precipitation. *Advanced Materials Research*. 496, 42-45.

Wang, H., Wang, X.j., Wang, W.s., Yan, X.b., Xia, P., Chen, J. and Zhao, J.f. (2016). Modeling and optimization of struvite recovery from wastewater and reusing for heavy metals immobilization in contaminated soil. *Journal of Chemical Technology and Biotechnology*. 91, 3045-3052.

Wang, J., Burken, J.G. and Xiaoqi, Z. (2006). Effect of Seeding Materials and Mixing Strength on Struvite Precipitation. *Water Environment Research*. 78, 125-132.

Warmadewanthi and Liu, J.C. (2009). Recovery of phosphate and ammonium as struvite from semiconductor wastewater. *Separation and Purification Technology*. 64, 368-373.

Wilsenach, J.A., Schuurbiers, C.A.H. and van Loosdrecht, M.C.M. (2007). Phosphate and potassium recovery from source separated urine through struvite precipitation. *Water Research*. 41, 458-466.

Wojciechowska, E. (2017). Potential and limits of landfill leachate treatment in a multi-stage subsurface flow constructed wetland – Evaluation of organics and nitrogen removal. *Bioresource Technology*. 236, 146-154.

Wu, L.-n., Liang, D.-w., Xu, Y.-y., Liu, T., Peng, Y.-z. and Zhang, J. (2016). A robust and cost-effective integrated process for nitrogen and bio-refractory organics removal from landfill leachate via short-cut nitrification, anaerobic ammonium oxidation in tandem with electrochemical oxidation. *Bioresource Technology*. 212, 296-301.

Xiu-Fen, L., Barnes, D. and Jian, C. (2011). Performance of struvite precipitation during pretreatment of raw landfill leachate and its biological validation. *Environmental Chemistry Letters*. 9, 71-75.

Xu, K., Wang, C., Liu, H. and Qian, Y. (2011). Simultaneous removal of phosphorus and potassium from synthetic urine through the precipitation of magnesium potassium phosphate hexahydrate. *Chemosphere*. 84, 207-212.

Yan, H. and Shih, K. (2016). Effects of calcium and ferric ions on struvite precipitation: A new assessment based on quantitative X-ray diffraction analysis. *Water Research*. 95, 310-318.

Ye, Z.-L., Chen, S.-H., Lu, M., Shi, J.-W., Lin, L.-F. and Wang, S.-M. (2011). Recovering phosphorus as struvite from the digested swine wastewater with bittern as a magnesium source. *Water Science & Technology*. 64, 334-340.

Yetilmezsoy, K. and Sapci-Zengin, Z. (2009). Recovery of ammonium nitrogen from the effluent of UASB treating poultry manure wastewater by MAP precipitation as a slow release fertilizer. *Journal of Hazardous Materials*. 166, 260-269.

Younes, M.K., Nopiah, Z.M., Basri, N.E.A., Basri, H., Abushammala, M.F.M. and Younes, M.Y. (2016). Landfill area estimation based on integrated waste disposal options and solid waste forecasting using modified ANFIS model. *Waste Management*. 55, 3-11.

Yusof, N., Haraguchi, A., Hassan, M.A., Othman, M.R., Wakisaka, M. and Shirai, Y. (2009). Measuring organic carbon, nutrients and heavy metals in rivers receiving leachate from controlled and uncontrolled municipal solid waste (MSW) landfills. *Waste Management*. 29, 2666-2680.

Yusof, N., Hassan, M.A., Phang, L.Y., Tabatabaei, M., Othman, M.R., Mori, M., Wakisaka, M., Sakai, K. and Shirai, Y. (2010). Nitrification of ammonium-rich sanitary landfill leachate. *Waste Management*. 30, 100-109.

Zhang, D.M., Chen, Y.X., Jilani, G., Wu, W.X., Liu, W.L. and Han, Z.Y. (2012). Optimization of struvite crystallization protocol for pretreating the swine wastewater and its impact on subsequent anaerobic biodegradation of pollutants. *Bioresource Technology*. 116, 386-395.

Zhang, Q., Zhao, S., Ye, X. and Xiao, W. (2016). Effects of organic substances on struvite crystallization and recovery. *Desalination and Water Treatment*. 57, 10924-10933.

Zhang, T., Ding, L. and Ren, H. (2009a). Pretreatment of ammonium removal from landfill leachate by chemical precipitation. *Journal of Hazardous Materials*. 166, 911-915.

Zhang, T., Ding, L., Ren, H. and Xiong, X. (2009b). Ammonium nitrogen removal from coking wastewater by chemical precipitation recycle technology. *Water Research*. 43, 5209-5215.

Zhou, S. and Wu, Y. (2012). Improving the prediction of ammonium nitrogen removal through struvite precipitation. *Environmental Science and Pollution Research*. 19, 347-360.