Environ. Eng. Res. 2016; 21(1): 29-35
http://dx.doi.org/10.4491/eer.2015.066

pISSN 1226-1025
eISSN 2005-968X

Struvite recovery from swine wastewater and its assessment as a fertilizer

Hong-Duck Ryu[1], **Sang-Ill Lee**[2†]

[1]Watershed and Total Load Management Division, National Institute of Environmental Research, Incheon 22689, Republic of Korea
[2]Department of Environmental Engineering, Chungbuk National University, Cheongju 28644, Republic of Korea

ABSTRACT

This study evaluated the fertilizing value of struvite deposit recovered from swine wastewater in cultivating lettuce. Struvite deposit was compared to complex fertilizer, organic fertilizer and compost to evaluate the fertilizing effect of struvite deposit. Laboratory pot test showed that the struvite deposit better enhanced lettuce growth in comparison to commercial fertilizers. It was revealed that the growth rate of lettuce was simultaneously controlled by phosphorus (P) and magnesium (Mg). Moreover, nutrients such as nitrogen (N), P, K, calcium (Ca) and magnesium (Mg) were abundantly observed in the vegetable tissue of struvite pot. Meanwhile, struvite application led to the lower accumulation of mercury (Hg), lead (Pb), chromium (Cr^{6+}) and nickel (Ni). In addition, no detection of cadmium (Cd), arsenic (As) and nickel (Ni) in the lettuce tissue was observed in struvite application pots. The experimental results proved that the optimum struvite dosage for lettuce cultivation was 0.5 g struvite/kg soil. The column experiments clearly showed that ammonia nitrogen was more slowly released from struvite deposit than from complex fertilizer. Consequently, it was concluded that the struvite deposits recovered from swine wastewater were effective as a multi-nutrient fertilizer for lettuce cultivation.

Keywords: Commercial fertilizer, Lettuce, Pot test, Struvite deposit, Swine wastewater

1. Introduction

Swine wastewater typically contains the high levels of ammonia nitrogen (NH_4-N) [1]. Among many treatment methods for NH_4-N in swine wastewater, struvite precipitation would be attractive due to its high removal efficiency in a very short reaction time, as revealed in many previous studies [2-5]. Struvite crystallizes as a white orthorhombic crystalline structure, which is composed of magnesium, ammonium, and phosphate in equal molar concentrations, by forming magnesium ammonium phosphate (Struvite, $MgNH_4PO_4 \cdot 6H_2O$).

However, a considerable amount of struvite sludge generated as a by-product during the removal of ammonium could cause another problem of waste disposal. A feasible solution to this problem would be the struvite reuse as a fertilizer because it is considered a recyclable, environmentally friendly and preferred fertilizer. Struvite contains theoretically 12.6% P, 5.7% N and 9.9% Mg. Specifically, the presence of Mg also made struvite useful for sugar beets [6]. Moreover, since struvite is slightly soluble in water and soil solutions, slow-release struvite has been found to be a highly effective source of phosphorus, nitrogen and magnesium for plants through both foliar and soil application [7].

Although struvite has been qualified as a fertilizer, struvite precipitate obtained from swine wastewater was never tested before as a fertilizer. A few fertilizer studies using struvite recovered from semiconductor wastewater, poultry manure wastewater and landfill leachate have been reported [8-11].

The present study, therefore, aims to investigate the feasibility of struvite precipitate recovered from swine wastewater as a fertilizer. Specifically, objectives of this study were to characterize precipitated struvite obtained from swine wastewater to evaluate the fertilizing value of struvite precipitate with pot trial tests for cultivation of Lactuca sativa (common lettuce) by comparing it with commercial fertilizers to determine the optimum dosage of struvite precipitate for cultivation to analyze the levels of nutrients and heavy metals in vegetables tissue grown with struvite and other fertilizers and to examine slow-release properties of struvite precipitate.

2. Materials and Methods

2.1. Struvite Recovery and Synthesis

The struvite deposit for experiments was recovered from a swine

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Received July 5, 2015 **Accepted** December 1, 2015

† Corresponding author
Email: gatorlee@chungbuk.ac.kr
Tel: +82-43-261-2469 Fax: +82-43-272-2469

wastewater. The swine wastewater from a piggery, which is located in Naesu, South Korea, was used for struvite crystallization and it was characterized in Table 1. Note that the swine wastewater had quite high influent concentration levels of ammonia nitrogen.

For struvite synthesis, struvite was recovered by following the method suggested by Kim et al. [12]. Magnesium chloride ($MgCl_2·6H_2O$) and potassium phosphate (K_2HPO_4) were used with the concentrations of 70 g Mg/L and 50 g P/L as the alternate sources of magnesium and phosphate, respectively. $MgCl_2·6H_2O$ and K_2HPO_4 were simultaneously added into struvite precipitation tank to reach at 1:1:1 in the molar ratio of NH_4-N:Mg:PO_4-P for struvite formation, and then pH adjustment of the wastewater to 9 was achieved by the continuous addition of NaOH 5 N. The pH 9 was optimal pH for achieving the highest NH_4-N removal in our previous batch experiments. According to the study conducted by Kim et al. [12], the NH_4-N removal efficiency in struvite precipitation was optimal at this feeding sequence of chemicals of magnesium, phosphate and buffering reagent [12]. The mixing speed in the struvite reaction tank was 250 rpm. The solution was allowed to settle in the jar for 5 min. In struvite precipitation, the NH_4-N removal efficiency was about 81% on average. The settled struvite deposit was collected and used as a multi-nutrient fertilizer for cultivating lettuce in our experiments. The collected struvite deposit was dried in the shade at room temperature for 7 days before being used in pot trial tests.

2.2. Pot Tests: Evaluation of Struvite Deposit as a Fertilizer

The fertilizing potential of struvite was evaluated by comparing it with that of popular Korean commercial fertilizers: complex fertilizer, organic fertilizer and compost. The compositions of struvite deposit and each commercial fertilizer are given in Table 2. The compost was consisted of organic matter 5%, nitrogen 0.1%, NaCl 1.0% and less than moisture content of 50% in weight percent. For the complex fertilizer, N, P, K, and Ca existed in the forms of $(NH_4)_2HPO_4$, K_2SO_4 and $Ca(NO_3)_2$, respectively.

Raw soil samples were taken from a local mountain in Cheongju and dried at room temperature for 15 days. The dried soil was sieved with maximum 1.2 cm prior to filling them in each pot. The soil classification was sandy loam and it was composed of 54.6% of sand, 33.3% of silt and 12.1% of clay. The soil pH was 5.3. Other important soil characteristics are provided in Table

Table 1. Characteristics of Raw Swine Wastewater

Parameter	Concentration range	Average
Suspended solid (SS) (mg/L)	1489-6831	4160
Total chemical oxygen demand (TCOD) (mg/L)	4391-5887	5139
Total Kjeldahl nitrogen (TKN) (mg/L)	748-1324	1036
NH_4-N (mg/L)	628-1061	844.5
NO_2-N (mg/L)	n.d.	n.d.
NO_3-N (mg/L)	n.d.	n.d.
Total phosphorus (T-P) (mg/L)	76-241	159
PO_4-P (mg/L)	23.6-37.6	30.6
TCOD/T-N	4.0-6.4	5.2
TCOD/T-P	24.2-53.8	39.0
pH	7.5-8.3	7.9

n.d.: not detected.

Table 2. Composition of Struvite Deposit and Commercial Fertilizers Used in Agricultural Tests

Elements	Complex fertilizer	Organic fertilizer	Struvite
N	11	5.0	14.8
O	n.m.	n.m.	34.0
Mg	4	9.3	10.2
Si	14	n.m.	n.m.
P	6	0.4	15.6
K	6	0.9	2.0
Ca	20	13.3	n.m.
B	0.1	n.m.	n.m.
C	n.m.	n.m.	20.0
Cl	n.m.	n.m.	3.4

Note: All indicated figures are based on weight percent (wt.%).
Note: In this table, compost was not included and its composition can be found in the text.
n.m.: not measured.

Table 3. Characteristics of Soil Used in Our Experiments

Items	T-N	T-P	K_2O	CaO	MgO	TCOD	TOC[a]
Concentration (g/kg soil)	0.908	0.572	0.151	0.286	0.048	6.9	4.2

[a] TOC indicates total organic carbon.

Table 4. Concentration of Heavy Metals in Soil, Commercial Fertilizers and Struvite Deposits

Items	Heavy metals (mg/kg)							
	Cd	Cu	As	Hg	Pb	Cr^{6+}	Zn	Ni
Soil	0.037	0.201	n.d.	n.d.	0.599	0.216	1.750	0.108
Complex fertilizer	0.038	0.452	0.156	n.d.	0.005	3.064	2.711	4.437
Organic fertilizer	0.036	4.028	n.d.	n.d.	0.157	0.398	8.843	0.229
Compost fertilizer	0.008	0.241	n.d	n.d.	0.022	0.098	0.139	0.044
Struvite	0.011	4.597	n.d.	n.d.	0.034	0.341	14.9124	0.072

n.d.: not detected

3. The concentrations of heavy metals in soil, commercial fertilizers and struvite are also presented in Table 4.

Five sets of three pots, for a total of 15 plastic pots, were prepared. Each plastic pot had 9 cm surface diameter and approximately 8 cm of working depth. 320 g of sieved soil was mixed with respective fertilizer sources and added to each pot. One set of 3 pots was used as control in which no fertilizer source was added. In other four sets, three commercial fertilizers and struvite deposit were added to achieve an equivalent concentration of 110 kg N/ha, respectively. This application rate was chosen based on a scientific recommendation made by the National Academy of Agricultural Science of Korea in growing lettuce. The amount of fertilizer needed to reach 110 kg N/ha was 0.26, 0.57, 28.3, 0.19 g for complex fertilizer, organic fertilizer, compost, and struvite deposit, respectively.

The pot tests were performed at room temperature. Fluorescent lightening was continuously supplied to the plants in order to maintain the specific intensity of illumination. Illuminances measured during the experimental period were between 5770 and 5850 lux (lx). Three seeds of lettuce were planted within the top 1.5 cm of soil in each pot. The room temperature of laboratory was 18.3˚C on average with the standard deviation of 1.5˚C during the experimental period. 25 mL of distilled waster was added in each pot every two days. Length of leaves was periodically recorded in each pot. After 63 days the plants were harvested from each pot and weighed before and after drying (in an oven set at 105˚C for 24 hours) to determine their fresh and dry weight. As conducted by Li and Zhao [8], the lettuce was sprayed with distilled water to wash the dust off prior to harvesting. The level of heavy metals and nutrients in dry vegetables were also analyzed.

2.3. Pot Tests: Determination of Optimum Struvite Dosage

The optimum struvite dosage for cultivating lettuce was determined. Six sets of three pots were filled with 250 g of sieved soil and struvite dosages of 0, 0.1, 0.2, 0.3, 0.5 and 0.6 g, which are equivalent to concentrations of 0, 0.4, 0.8, 1.2, 2.0 and 2.4 g struvite/kg soil, respectively. Three seeds of lettuce were sowed within the top 1.5 cm of soil in each pot. The room temperature was 19.0˚C on average with the standard deviation of 2.0˚C during the experimental period. Fluorescent lightening was also supplied to the plants in order to maintain the intensity of illumination. Illuminances were between 5670 and 5780 lux (lx). 25 mL of distilled waster was added in each pot every two days. Length of leaves was periodically recorded for each pot. After 54 days the plants were harvested and weighed to determine their fresh and dry weight.

2.4. Assessment of Slow-Release Properties

A laboratory column test was designed to evaluate a slow-release characteristic, specifically nitrogen-leaching behavior, of struvite deposit compared to those of complex fertilizer. Two identical glass columns were prepared. Each column was 30 cm in height and 5 cm in diameter. The complex fertilizer of 454.55 mg and dried struvite deposit of 337.84 mg were each mixed with 500 g of sieved soil, and packed into two separate columns. The applied amount of complex fertilizer and struvite deposit was at an equivalent concentration of sieved soil 100 mg N/kg. Tap water was supplied downward with the flow rate of 20 mL/min in each column for 40 h. The effluent liquid volume and effluent NH_4-N concentration from each column were periodically measured to calculate the cumulative nitrogen mass.

2.5. Analytical Procedures

The suspended solid (SS) (standard code: 2540 D), Total chemical oxygen demand (TCOD) (standard code: 5220 D), total Kjeldahl nitrogen (TKN) (standard code: 4500-N B), NO_2-N (standard code: 4500-NO_2^- B), NO_3-N (standard code: 4500-NO_3^- B) and PO_4-P (standard code: 4500-P E) in all samples were analyzed by the Standard Methods for examination of water and wastewater [13]. NH_4-N and total phosphorus (T-P) were analyzed using DR4000 spectrophotometer with relevant Hach regents as provided by the Hach manual (Hach Company, USA).

For soil characteristics analysis, 10 g of sieved soil sample was placed in a 100 mL Pyrex tube containing 50 mL of HCl 0.1 N. The mixture was heated at 100˚C for 1 h. After the temperature cooled down naturally, 10 mL of HNO_3 5% was added into the tube and mixed using a vortex. The mixture was then centrifuged at 1448 g for 15 min. The supernatant was filtered with 0.45 μm membrane filter. Then T-N, T-P, K_2O, CaO, MgO and organic carbon (as COD) were analyzed. T-N (standard code: 4500-N) was determined according to the procedure described in Standard Methods for examination of water and wastewater [13]. The analyses of K_2O, CaO and MgO were performed by inductively coupled plasma-atomic emission spectrometry (ICP-AES 3300DV; Perkin Elmer, USA).

Heavy metals, which are contained in dry vegetable, were also measured by ICP-AES (Perkin Elmer, USA) after acidic digestion. In digestion, the dry vegetable samples were placed in a Pyrex tube containing 4 mL of conc. HNO_3. The mixture was heated at 200˚C until dry. After the temperature cooled down naturally, 20 mL of HNO_3 5% was added into the tube and heated at 50˚C for 20 min. When the sample temperature was cooled down to room temperature, the solution in each tube was evaluated using ICP-AES. The minimum detection limit of ICP-AES for measuring Cd, Cu, As, Hg, Pb, Cr, Zn and Ni was 0.002, 0.001, 0.0002, 0.0909, 0.004, 0.002, 0.0015 and 0.003 mg/L, respectively.

The compositions of commercial fertilizers and dried struvited deposits were analyzed using energy dispersive analysis (EDS) of X-rays. Additionally, X-ray diffraction (XRD, Model DMS 2000 system; SCINTAG) was used to further characterize the dried struvite deposit obtained from swine wastewater.

3. Results and Discussion

3.1. Recovery of Struvite Deposit

XRD analysis was also used to characterize the purity of struvite deposits collected from swine wastewater. The X-ray diffractograms exhibited several peaks indicative of the struvite presence as illustrated in Fig. 1. The XRD pattern generated from the precipitated matters matched with the database model for struvite, i.e., position and intensity of the peaks. The high purity of struvite deposits would be due to the high NH_4-N removal of 81%.

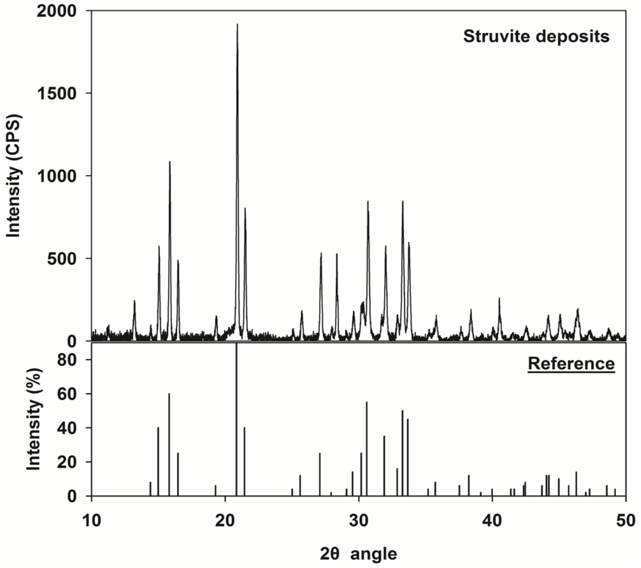

Fig. 1. XRD diffractograms of the precipitated matters.

3.2. Fertility Evaluation of Struvite Deposit

The obtained struvite deposits were utilized in cultivation tests and compared with that of commercial fertilizers to assess its fertility. During the experimental period of 63 days, the tallest leaf in each pot was selected and measured. Fig. 2 illustrates that the lettuce grew at different rates depending on fertilizing sources. On 63nd days, the average leaf length of lettuce in control, complex fertilizer, organic fertilizer, compost and struvite pots reached 12, 28, 25, 17 and 50 mm, respectively, as presented in Fig. 2(a). After 63 days, the plants from each pot were harvested and weighed before and after drying to determine their fresh and dry weights. As evident from Fig. 2(b), it was clear that the addition of struvite significantly increased the average fresh and dry weights of lettuce than control. Also, the average fresh and dry weights of lettuce in struvite pots ranked the best in the experimental group. The fresh and dry weights of lettuce decreased in order of struvite > complex fertilizer > organic fertilizer > compost > control pot. This finding is further supported by data in Fig. 2(a), where the longest leaf was also found in the same order. It is well documented by previous studies that the vegetables grown in struvite pots have had much higher growth rates than control pots (without addition of external nitrogen and phosphorus) [8, 9, 14, 15]. The difference of growth level according to the kind of fertilizer would be due to the amount of nutrients applied to the soil. Fig. 3 clearly illustrated that the growth rates of leaves according to five different fertilizing sources including "control" were determined by the concentration product of phosphorus (P) and magnesium (Mg) applied to the soil. In other words, Fig. 3(d) highlights that P and Mg were key elements in the growth rates of lettuce. Meanwhile, a correlation between the leaf growth rate and concentration product of (P)(K)(Mg) or (P)(K) was relatively weak (see Fig. 3(a) and 3(b)). It indicates that the leaf growth rate of lettuce was less affected by K. It would be more simple approach to show correlation between a single nutrient (e.g., P, Mg, K) and the growth rate rather than between the concentration product of nutrients and the growth rate. However, it would be more rational to present

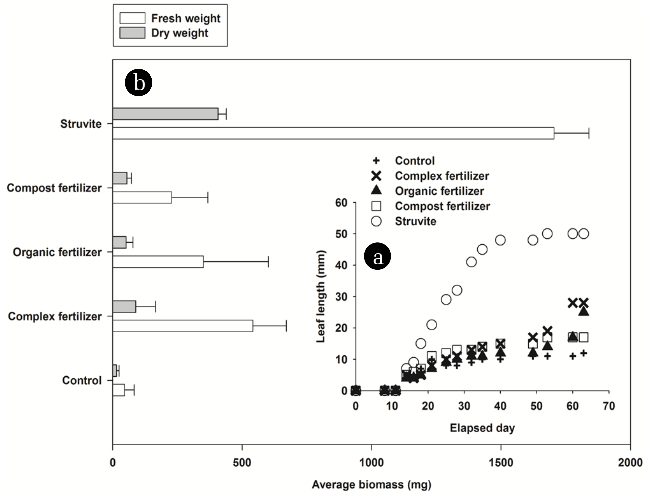

Fig. 2. Temporal variation of leaf length (a) and fresh and dry weight of lettuce after 63 days growth (b) depending on fertilizing sources: error bars indicate standard deviation.

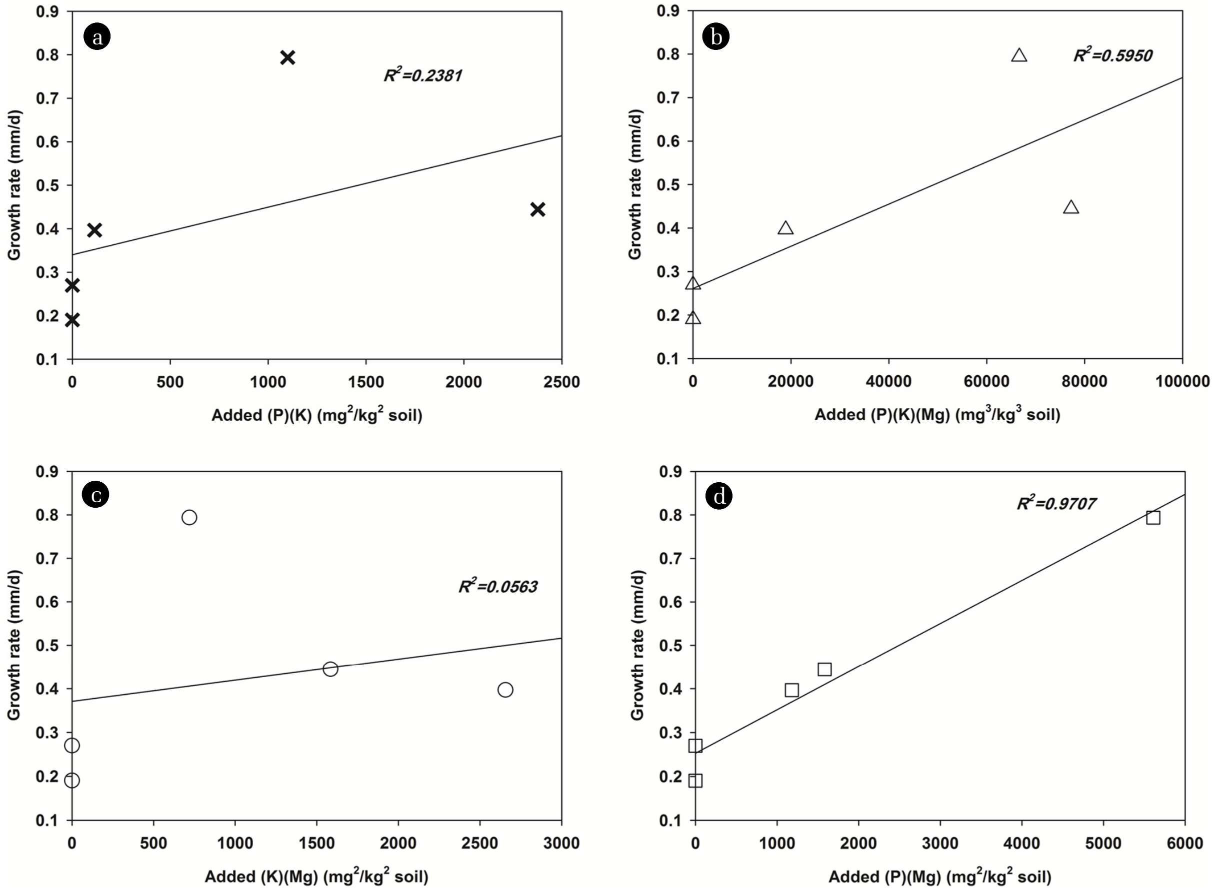

Fig. 3. Effect of concentration product on leaf growth rate depending on fertilizing sources.

mutual dependence among nutrients because the growth rates of leaves would be reciprocally affected by several elements. It is inferred that K found in struvite deposits would be present as a potassium magnesium phosphate ($KMgPO_4 \cdot 6H_2O$, struvite-K) which can be formed as a by-product material in the process of struvite precipitation. The previous studies also support our experimental finding. From a previous study by Wilsenach et al. [16], it was reported that struvite as well as struvite-K were successfully precipitated from source separated urine through struvite precipitation. Furthermore, Sun et al. [17] also reported that the simultaneous precipitation of struvite and struvite-K was observed in goats during onset of urolithiasis.

3.3. Heavy Metals and Nutrients in Vegetable Tissue

Heavy metals could be a great concern in agronomic field when the recovered struvite is applied as a fertilizer. It was observed that the contents of Cu, Cr and Zn in the struvite precipitate were higher than those in the raw soil, while the contents of other metals in the struvite precipitate were lower than those in the raw soil, as shown in Table 4. It means that there would not be any concern of heavy metal contamination if the struvite precipitate into the soil. The heavy metal levels were also compared to evaluate the accumulation degree of heavy metals in lettuce tissue. Table 5 shows that heavy metals including copper (Cu), mercury (Hg), lead (Pb), chromium (Cr^{6+}) and zinc (Zn) were contained in all samples, whereas cadmium (Cd) and arsenic (As) were not detected. Similarly, no detection of Cd and As in application of struvite to vegetable cultivation was reported in the previous study in which struvite recovered from landfill leachate was used in growing vegetables [8]. For Cu and Hg, their concentrations in struvite pots were similar with other fertilizer pots, although they were higher than those in control pots. For Pb and Cr^{6+} and Ni, their levels in struvite pots were lower than in other fertilizer pots. It was interesting to observe that the heavy metals level in the lettuce tissue growing in the chemical fertilizer pots was higher than those growing in the struvite pots, except for Cu and Zn contents. Similar result was also observed in the study of Li and Zhao [8]. In their study, the metals level of Cr, Pb, Zn and Ni in the vegetables growing in a model fertilizer pots (N&P pots) was slightly higher than those growing in the struvite pots. Meanwhile, it is wonder why the different heavy metal uptake occurred depending on fertilizing sources. It would be due to that each fertilizing source has different solubility properties. It would be required that heavy metal uptake based on solubility of fertilizer be further studied. In summary, lettuce tissue of struvite pots did not have such high level of heavy metal concentration compared to other commercial fertilizer. Liu et al. [7] also showed that the heavy metal content in the recovered struvite

Table 5. Concentration of Heavy Metals in Dried Lettuce Tissue

Pot	Heavy metals (mg/kg dry vegetable)							
	Cd	Cu	As	Hg	Pb	Cr^{6+}	Zn	Ni
Control	n.d.	11.8 (±2.3[a])	n.d.	0.5 (±0.1)	8.1 (±2.1)	6.8 (±1.4)	72.8 (±5.3)	0.5 (±0.1)
Complex fertilizer	n.d.	22.8 (±3.1)	n.d.	1.3 (±0.4)	11.1 (±1.6)	9.4 (±2.5)	13.0 (±1.9)	1.6 (±0.8)
Organic fertilizer	n.d.	19.2 (±1.6)	n.d.	1.4 (±0.2)	8.5 (±2.4.)	8.3 (±1.6)	107.0 (±10.1)	0.6 (±0.1)
Compost fertilizer	n.d.	19.3 (±1.8)	n.d.	1.1 (±0.3)	9.9 (±1.7)	6.7 (±2.2)	12.0 (±1.6)	0.6 (±0.1)
Struvite	n.d.	20.5 (±4.5)	n.d.	0.9 (±0.2)	4.5 (±1.3)	4.2 (±2.1)	68.0 (±5.5)	n.d.

n.d.: not detected

[a] Standard deviation

Table 6. Concentration of Nutrients in Dried Lettuce Tissue

Pot	Nutrients (mg/kg dry vegetable)				
	T-N	P_2O_5	K	Ca	Mg
Control	1683 (±15[a])	94 (±13)	2104 (±121)	95 (±16)	29 (±2)
Complex fertilizer	4954 (±105)	130 (±25)	3235 (±225)	473 (±95)	58 (±5)
Organic fertilizer	4218 (±203)	108 (±20)	2802 (±131)	408 (±101)	72 (±4)
Compost fertilizer	4586 (±215)	107 (±11)	3543 (±243)	482 (±97)	49 (±5)
Struvite	7117 (±367)	313 (±16)	3737 (±251)	287 (±12)	105 (±7)

[a]Standard deviation

from wastewater was below the legal limits as a fertilizer. It indicates that the cultivation of lettuce with struvite deposit recovered from swine wastewater could be safe.

Meanwhile, the availability of nutrients from struvite and commercial fertilizers was estimated by investigating nutrients contained in the tissue of lettuce. Table 6 shows that the harvested leaves from struvite pots contained relative high concentration of N, P, K and Mg. The control pots had the lowest concentration of N, P, K, Ca and Mg compared to other pots. It is interesting to observe that P and Mg concentration in struvite pots was much higher than that in commercial fertilizer pots. As revealed in Fig. 3, the finding that the growth rates of leaves were determined by the concentration product of phosphorus (P) and magnesium (Mg) applied to the soil could be proved by much more uptake of P and Mg in struvite pots.

3.4. Effect of Struvite Dosage on Lettuce Cultivation

The optimum struvite dosage for cultivating lettuce was determined. During the experimental period of 54 days, the leaf length of lettuce was periodically measured. The agricultural tests showed that the lettuce grew at different rates as a function of applied struvite dosage as illustrated in Fig. 4. Fig. 4(a) shows that the leaf length of lettuce increased as the struvite dosage increased from 0 to 0.5 g struvite/kg soil. However, no additional growth was observed when struvite dosage was increased over 0.5 g struvite/kg soil. Similar trend was also observed in the lettuce biomass based on dry weight as shown in Fig. 4(b). The test results of dry weight show that increasing struvite dosage up to 0.5 g struvite/kg soil has positive effect on biomass, but ineffective beyond that. However, the fresh weight increased with increasing struvite dosage from 0.5 to 0.6 g. These findings were supported by the study of Li and Zhao [8]. They explained that increasing the amount of struvite, which is recovered from landfill leachate, could further stimulate the growth of water convolvulus.

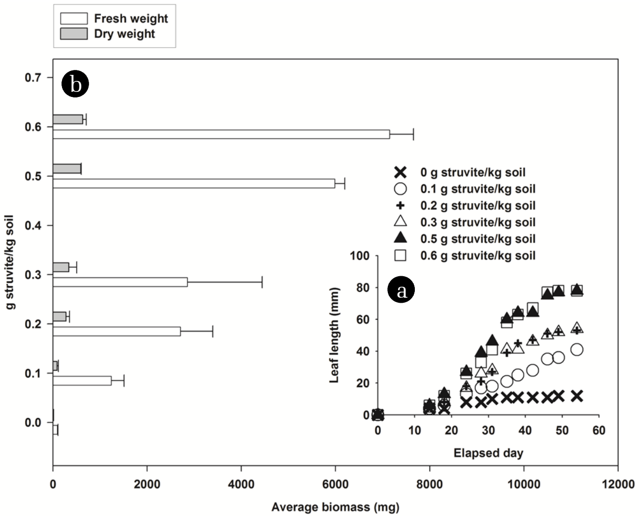

Fig. 4. Temporal variation of leaf length (a) and fresh and dry weight of lettuce after 54 days growth (b) as a function of applied struvite dosage: error bars indicate standard deviation.

3.5. Slow-Release Properties of Struvite Deposit

The ammonia nitrogen leaching from the mixtures of soil-complex fertilizer and soil-struvite was compared by column tests. In the lab-scale continuous column tests for 40 h, nitrogen was more slowly leached from struvite deposit than complex fertilizer as given in Fig. 5. As two hours have passed since the start of experiment, nitrogen was rapidly washed out from the complex fertilizer column, whereas it was slowly leached from the struvite deposit column. In addition, the time needed to reach steady state for struvite deposit was longer than that for complex fertilizer. This means that the struvite recovered from swine wastewater had

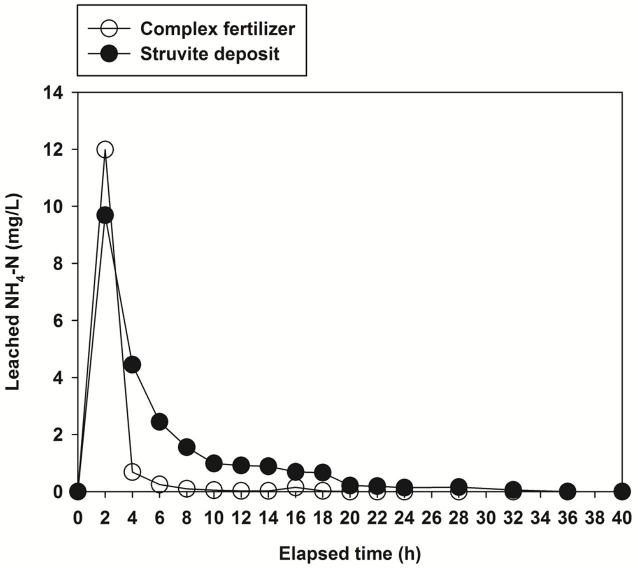

Fig. 5. Comparison of complex fertilizer and struvite deposit for leached NH_4-N as a function of elapsed time.

better slow-release property than complex fertilizer. These results can be explained why struvite pots better facilitate the lettuce growth compared to complex fertilizer as illustrated in Fig. 2.

4. Conclusions

Struvite recovered from swine wastewater was applied in cultivation of lettuce. The fertilizing value of struvite was evaluated by comparing it with commercial fertilizers by pot trial tests. Based on the experimental results, the following conclusions were drawn:

(1) The capability of struvite as a fertilizer far surpassed other commercial fertilizers during the experimental period of 63 days. Also, it was revealed that the growth rate of lettuce was greatly affected by the amount of P and Mg.

(2) In the investigation of heavy metal effects on the lettuce growth, the application of struvite resulted in less accumulation of Hg, Pb, Cr^{6+} and Ni in vegetable tissue than commercial fertilizers. Moreover, Cd, As and Ni were not detected in struvite pots.

(3) It was found that the struvite source provided the essential crop nutrients of N, P, K, Ca and Mg for lettuce as much as other commercial fertilizers. Specifically, much more amount of P and Mg was observed in the vegetable tissues of struvite pots.

(4) It was revealed that the lettuce growth rate increased as struvite dosage increased. The optimum dosage was 0.5 g struvite/kg soil and any additional dosage over the optimum amount did not cause more growth of lettuce.

(5) The lab-scale column tests clearly showed that the struvite deposits have higher slow-release property of NH_4-N than complex fertilizer.

(6) Consequently, it was proved that struvite deposits, recovered from swine wastewater were effective as a multi-nutrient fertilizer in cultivating lettuce.

References

1. Lin SJ, Kim TH. Removal of organic matter and nitrogen in swine wastewater using an integrated ion exchange and bioelectrochemical system. *Bioresour. Technol.* 2015;189:107-112.
2. Ryu H, Lee S. Application of struvite precipitation as a pretreatment in treating swine wastewater. *Process Biochem.* 2010;45:563-572.
3. Huang H, Xu C, Zhang W. Removal of nutrients from piggery wastewater using struvite precipitation and pyrogenation technology. *Bioresour. Technol.* 2011;102:2523-2528.
4. Liu Y, Kwag J, Kim J. Ra C. Recovery of nitrogen and phosphorus by struvite crystallization from swine wastewater. *Desalination* 2011;277:364-369.
5. Zhang D, Chen Y, Jilani G, Wu W, Liu W, Han Z. Optimization of struvite crystallization protocol for pretreating the swine wastewater and its impact on subsequent anaerobic biodegradation of pollutants. *Bioresour. Technol.* 2012;116:386-395.
6. de-Bashan LE, Bashan Y. Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997-2003). *Water Res.* 2004;38:4222-4246.
7. Liu Y, Kumar S, Kwag JH, Ra C. Magnesium ammonium phosphate formation, recovery and its application as valuable resources: a review. *J. Chem. Technol. Biotechnol.* 2013;88:181-189.
8. Li XZ, Zhao QL. Recovery of ammonium-nitrogen from landfill leachate as a multi nutrient fertilizer. *Ecol. Eng.* 2003;20:171-181.
9. Yetilmezsoy K, Sapci-Zengin Z. Recovery of ammonium nitrogen from the effluent of UASB treating poultry manure wastewater by MAP precipitation as a slow release fertilizer. *J. Hazard. Mater.* 2009;166:260-269.
10. Ryu H, Lim C, Kang, M, Lee S. Evaluation of struvite obtained from semiconductor wastewater as a fertilizer in cultivating Chinese cabbage. *J. Hazard. Mater.* 2012;221-222:248-255.
11. Ryu H, Lim C, Kim Y, Kim K, Lee S. Recovery of struvte obtained from semiconductor wastewater and reuse as a slow-release fertilizer. *Environ. Eng. Sic.* 2012;29:540-548.
12. Kim D, Ryu HD, Kim MS, Kim J, Lee SI. Enhancing struvite precipitation potential for ammonia nitrogen removal in municipal landfill leachate. *J. Hazard. Mater.* 2007;146:81-85.
13. APHA, AWWA, WEF. Standard methods for the examination of water and wastewater. 21st ed. Washington DC: National Government Publication; 2005.
14. Diwani GE, Rafie SE, Ibiari NNE, El-Aila HI. Recovery of ammonia nitrogen from industrial wastewater treatment as struvite slow releasing fertilizer. *Desalination* 2007;214:200-214.
15. Ganrot Z, Dave G, Nilsson E, Li B. Plant availability of nutrients recovered as solids from human urine tested in climate chamber on Triticum aestivum L. *Bioresour. Technol.* 2007;98:3122-3129.
16. Wilsenach JA, Schuurbiers CAH, van Loosdrecht MCM. Phosphate and potassium recovery from source separated urine through struvite precipitation. *Water Res.* 2007;41:458-466.
17. Sun WD, Wang JY, Zhang KC, Wang XL. Study on precipitation of struvite and struvite-K crystal in goats during onset of urolithiasis. *Res. Vet. Sci.* 2010;88:461-466.