IJAAR 7 (2019) 89-97 ISSN 2053-1265

International Journal of Advance Agricultural Research
www.bluepenjournals.org/ijaar

doi.org/10.33500/ijaar.2019.07.006

Utilization of recovered struvite from mixed wastewater of human urine and municipal sewage as an innovative fertilizer

Guoqi Wen[1,2], Lijuan Huang[1], Xiangru Zhang[1] and Zhengyi Hu[1,3]*

[1]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100049, China.
[2]Department of Soils and Agri-Food Engineering, Université Laval, Quebec, G1V 0A6, Canada.
[3]Research Centre for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China.

Article History
Received 21 March, 2019
Received in revised form 09 April, 2019
Accepted 15 April, 2019

Keywords:
Struvite,
Phosphorus,
Nutrients,
Heavy metals,
Vegetable.

Article Type:
Full Length Research

ABSTRACT

Struvite (MAP) recovered from a mixed wastewater of human urine and municipal sewage through a novel two-step precipitation method was well developed, but its fertilizer value to crops have not been investigated. The objective of this study was to explore the feasibility of using MAP as a fertilizer in cultivating Chinese cabbage (*Brassica rapa* L. ssp. *pekinensis*) by comparing with single superphosphate (SSP). A greenhouse experiment was conducted with the rate of 0.4 g P_2O_5 per pot and an unfertilized control. The dry mass and concentrations of nitrogen (N), phosphorus (P), and metal elements in vegetable shoots, soil after harvesting vegetables, and soil solutions were studied. Results showed that the average dry masses of vegetable shoots were 1.21, 1.46 and 1.67 g for the control, SSP, and MAP, respectively, which indicated that P fertilization significantly promoted the cabbage growth. The higher yield of Chinese cabbage caused by MAP application was also attributed to the Mg and K addition along with MAP fertilization. The concentrations of heavy metals in shoots, such as Cr and Cd, supplied with MAP were lower than that with SSP, which both were within the Chinese food safety criterion (GB2762-2017). Additionally, MAP supply seemed to increase soil fertility after the cabbage harvesting. The less progressing decrease of the N and P concentrations in soil solution with increasing sampling dates indicated that MAP was a promising slow-releasing fertilizer when compared to SSP. Based on these findings, it was concluded that MAP is an effective, promising, and economic P fertilizer for cultivating cabbage.

INTRODUCTION

Phosphorus (P) is a necessary nutrient for crop growth (Schroeder et al., 2013). However, approximately 30–40% of the arable land worldwide is P deficient (Kirkby and Johnston, 2008). Although most agricultural soils contain a considerable amount of P, only a small fraction (<1%) of it can be assimilated directly by plants (Frossard et al., 2011). The low availability of P is due to the fact that it readily forms insoluble complexes with calcium and magnesium (Balemi and Negisho, 2012). On the other hand, P lost through surface runoff is also an important contributor to the available soil P deficiency (Schroeder et al., 2004). Available soil P can be replenished repeatedly to meet crop demand by applying external P fertilizers, such as ammonium phosphate and single superphosphate (SSP), to feed the ever-increasing world population (Balemi and Negisho, 2012). At present, most of these P fertilizers are directly derived from phosphate rock, which is causing the global phosphate rock reserves

---

*Corresponding author. E-mail: zhyhu@ucas.ac.cn.

to dwindle annually. Cordell et al. (2009) estimated that the depletion timeline of phosphate rocks is limited to 100 years. Additionally, P lost from agricultural farms is a major contributor to surface water eutrophication (Correll, 1998). Therefore, recovering P from wastewaters and then using it as a P fertilizer in agriculture makes it more valuable and more attractive in terms of both agricultural production and environmental protection.

Many P recovery approaches have been developed for decades. As one of the promising techniques, struvite (MAP) precipitation from wastewater streams has been well determined in previous publications (Stratful et al., 2001; Liu et al., 2013). This method is effective in removing the phosphate and ammonium from wastewaters, and the recovered deposits contain higher levels of P_2O_5 and fewer impurities when compared with commercial P fertilizers (Liu et al., 2016). To date, P has been recovered through MAP precipitation in many waste streams, such as animal manures (Greaves et al., 1999), human urine (Liu et al., 2013), and municipal wastewaters (Doyle and Parsons, 2002). In these wastewaters, human urine and municipal sewage are two principal P sources. Rahman et al. (2014) reported that about 34% of P in wastewaters is originally from sewage. Human urine accounts for up to 50–80% of P in domestic wastewater (Larsen and Gujer, 1996). Approximately 11% of global P demand would be met if the P in human urine and municipal sewage was completely recovered (Mihelcic et al., 2011). Recovery of P through MAP precipitation from wastewater and then use it as an agricultural fertilizer have become more and more interesting for crop growers and researchers. Mehta et al. (2018) reported that MAP recovered from anaerobically digested effluent of sewage wastewater treatment plant was ineffective for the maize (*Zea mays* L.) growth because the $Mg(OH)_2$ reduced the P availability. However, Uysal et al. (2014) observed that MAP obtained from yeast industry anaerobic effluent was appropriate for both maize and tomato plants. Uysal and Kuru (2015) also observed that MAP recovered from dairy industry wastewater was beneficial to the growth of maize plants and was an effective fertilizer. Based on these results, it is essential to evaluate the MAP availability as a fertilizer when it is recovered from specific wastewaters.

In our previous study, a two-step precipitation method was demonstrated to recover high-quality MAP deposits from the mixed wastewater of human urine and municipal sewage without the addition of Mg (Wen et al., 2018). The recovered MAP has been qualified as a high-grade fertilizer based on the regulatory limit for mineral P fertilizer in China (GB/T 23349-2009). However, its real fertilizing effects on crop growth have not been investigated. The objective of this study was to investigate the feasibility of MAP derived from a mixture of human urine and municipal sewage as a fertilizer in cultivating Chinese cabbage by comparing with a commercial fertilizer SSP. Specifically, the impacts of MAP fertilization on cabbage biomass, tissue quality, and soil fertility were investigated. The hypothesis of this study was that MAP application could increase the yield and improve the quality of Chinese cabbage compared to SSP fertilizer.

MATERIALS AND METHODS

Phosphorus sources and soil characteristics

The fertilizer SSP (No. 42188862117) was purchased from DEWODUOFEILIAO. Inc., Nanjing, China. This SSP consisted of 0.4% N, 13% P_2O_5, 0.9% Mg, 15% Ca, and 0.6% K_2O. The MAP precipitate was recovered from the mixed wastewater of human urine and municipal sewage through a novel two-step precipitation method with the volume ratio of urine to municipal sewage of 0.05 (first step) and 0.2 (second step), stirring speed of 180 r min^{-1}, and hydraulic retention time of 30 min (Wen et al., 2018). This MAP contained higher levels of N (9%), P (15% P_2O_5), and Mg (5.2%), but lower concentrations of Ca (2%) and K_2O (0.5%) compared with the SSP. The other characteristics of MAP and SSP were listed in Table 1.

The soil used in the present study was collected from an agricultural experimental demonstration station located in Shunyi, Beijing with a depth of 0 to 15 cm and then grounded in a porcelain mortar and passed through a 2 mm sieve. This soil was sandy loam with a pH (in water) of 7.6. The mineral-N (NO_3-N and NH_4-N) was determined immediately after the soil was collected from the station. The Olsen-P and total phosphorus (TP) concentrations were 44 mg kg^{-1} and 0.67 g kg^{-1}, respectively. The mineral-N and total N (TN) concentrations were 79 mg N kg^{-1} and 0.95 g N kg^{-1}, respectively. The concentration of particulate organic matter was 13 mg kg^{-1}. The micronutrient and heavy metal contents in the soil were listed in Table 1.

Experimental design and management

A pot experiment was carried out and Chinese cabbage was used as the test crop. Each plastic pot was 21.3 cm in height and 20 cm in diameter. The MAP and SSP were used as P sources with rate of 0.4 g P_2O_5 per pot, that is, 0.2 g P_2O_5 per kilogram soil (Liu et al., 2016) and an unfertilized control was also arranged. To make the vegetable grown in a nutrient sufficient circumstance, the N and K fertilizers were applied at planting in the form of ammonium sulfate (22-0-0) and potassium chloride (0-0-60) at rates of 0.2 g N per kilogram soil and 0.1 g K_2O per kilogram soil, respectively. Before planting, 2-kilogram ground soil was filled into each plastic pot without any drainage hole. The vegetable seeds, which were disinfected with 2% H_2O_2 for two days, were planted at 2 cm in depth, then the three fertilizers were homogeneously

Table 1. Characteristics of pre-planting soil, SSP and MAP used in this experiment (Part I) and the added amount of chemicals, including nutrients and metal elements, to the pots along with the application of MAP and SSP (Part II).

Items	pH	TN	TP	Mg	Ca	K	Fe	Zn	Cr	Cd	Pb	Cu
Part I												
		g/kg						**mg/kg**				
Soil	7.58	0.95	0.67	1.32	6.97	16.97	17.17	54.24	65.10	0.93	18.60	16.57
SSP	1.80	4.36	57.23	8.72	147.99	4.23	5.81	55.94	22.60	n.d.	n.d.	26.79
MAP	6.39	94.05	65.04	52.41	17.23	5.25	4.44	26.28	n.d.	n.d.	n.d.	16.56
Part II												
		mg/pot										
SSP		11.73	174.56	26.60	451.36	11.38	17.72	0.18	0.06	n.d.	n.d.	0.08
MAP		253.00	174.96	140.96	46.34	16.02	11.94	0.08	n.d.	n.d.	n.d.	0.04

TN, total nitrogen; TP, total phosphorus; n.d., not detected. Two kilograms soil was filled in each pot.

broadcasted on the surface. Finally, 0.5 L deionized water was irrigated to each pot after planting. Twelve seeds were planted in each pot on September 1, 2017, and three seedlings with similar growth conditions were left when seedlings emerged from the ground on September 4, 2017. The pots were irrigated regularly with deionized water to maintain a level of 70% soil-water holding capacity which was measured each day with a hygrometer (Testo 608-H1, Germmany). The vegetables were harvested on October 13, 2017. No insecticide or pesticide was used throughout the vegetable growing period. The temperature ranged from 26±2°C and illumination intensity (photoperiod varying from 13 h 04 m to 11 h 15 m based on Beijing weather station) in the greenhouse was naturally controlled. Four replications were arranged for each treatment.

Sample collection and chemical analysis

Soil solution was sampled every two weeks using a soil moisture sampler (CSS 19.21.24F-10cm, Rhizon, Netherlands). The pH of soil solution was measured using a HI98185A type pH meter (Seven2Go, Mettler Toledo, Switzerland). The mineral-N and soluble-P were measured by colorimetric analysis according to the standard methods of the American Public Health Association (1998). The metal elements in the soil solution were measured with an inductively coupled plasma-optical emission spectrometer (ICP-OES) (Leeman Prodigy, USA).

The vegetables were harvested at 42 days after planting. Then, the whole plants were partitioned into two components (shoots and roots) and the biomass and chemical properties of the above-ground shoot were determined after being dried in a forced-draft oven at 70°C for 72 h. The fresh and dry masses of the above-ground shoots were measured before and after being oven-dried to calculate the tissue moisture. The dried shoots were ground with a grinder (FW80, Yongguangming, Beijing, China) and passed through a 2 mm sieve. Approximately 100 mg dry samples were dissolved in hydrochloric acid and nitric acid with a volume ratio of 3:5. The TP and metal elements were determined using an ICP-OES (Leeman Prodigy, USA), while TN was analyzed with an Elementar CN analyzer (Elementar, model Varian Macro CN, Hanau, Germany).

A 100 g soil subsample was used to determine the mineral-N after extracted by 1 M KCl (Maynard and Kalra, 1993). The soil NH$_4$-N was determined colorimetrically by reaction with nitroprusside (Nkonge and Balance, 1982), while NO$_3$-N was measured at 210 nm by liquid chromatography on a Dionex 4000i equipped with a VDM-II UV-V detector (Dionex Corporation, Sunnyvale, CA, USA). The pH was measured in a 1:2.5 ratio of soil/distilled water using a HI98185A type pH meter (Seven2Go, Mettler Toledo, Switzerland). The Olsen-P was extracted with 0.5 M NaHCO$_3$ and analyzed using the molybdenum blue colorimetric method (Lu, 1999). Soil TN was measured by dry combustion with an Elementar CN analyzer (Elementar, model Varian Macro CN, Hanau, Germany). The TP and metal elements were extracted with hydrochloric acid, nitric acid, and hydrofluoric acid with a volume ratio of 1:1:1 and then analyzed using ICP-OES.

Statistical analysis

In this study, we used a generalized mixed model to analyze the data by considering the P source as a fixed effect and replication as a random effect. Regarding the chemical characteristics of the soil solution, the sampling date was proposed as a repeated measurement in this model. When a significant effect in the ANOVA tables was observed, we used the protected LSD multiple

Table 2. Effects of P source on the dry mass and the concentrations of TN, TP, and metal elements in the cabbage shoot.

Source of variance	Dry mass	Moisture	TN	TP	K	Mg	Ca	Fe	Zn	Cd	Cr	Cu
	p-values											
P source	*	ns[†]	***	***	**	***	ns	ns	ns	ns	**	ns
	----- g ----	--%--	--------------- g/kg dry mass --------------					-------------- mg/kg dry mass -------------				
Control	1.21a[‡]	97.13	25.5b	5.5b	32.00b	3.4b	24.05	0.19c	64.91	0.93	10.70a	8.58
SSP	1.46ab	97.06	28.6b	7.5a	35.90b	3.7b	25.66	0.29a	59.35	1.02	9.47a	8.36
MAP	1.67b	96.97	42.0a	7.6a	53.26a	5.7a	23.17	0.25a	63.89	0.97	6.78b	8.79

*, **, *** represent the significant level at α= 0.05, 0.01, and 0.001, respectively. [†]ns, not significant at α= 0.05. [‡]Mean values followed the same letter within a column are not significantly different at α= 0.05. The SSP and MAP indicate the SSP and MAP, respectively.

comparisons to check the significant difference of the corresponding chemical characteristics among treatments.

The Shapiro-Wilk was used to test the normality assumption on the residuals of each model, while residual plots were used to verify the homogeneity of variances. When the normality assumption was not met, response variables were transformed using the Box-Cox approach.

In order to explore the potential factors in the promotion of vegetable biomass, the Pearson's correlation analysis was used to investigate the relationship between the dry mass and the concentrations of nutrients and metal elements of the above-ground shoots. All analyses were performed using the SAS Mixed procedure (SAS Inc., NC, version 9.4) at a significant level of α= 0.05. All results were marked with *, **, and ***, which indicted the significance at α =0.05, 0.01, and 0.001, respectively.

RESULTS

Cabbage shoot

Dry mass and moisture percentage

The P fertilization significantly promoted the cabbage growth and its dry mass reached a maximum of 1.67 g when MAP was used (Table 2). However, no obvious alteration in shoot moisture percentage was observed when different P sources were applied. The average moisture percentages for the unfertilized control, SSP, and MAP were 97.13, 97.06, and 96.97%, respectively (Table 2).

Nutrients and metal elements

Phosphorus fertilization significantly affected the TN and TP concentrations of cabbage shoots which respectively increased from 25.52 and 5.51 mg kg^{-1} dry mass at unfertilized control to maximum levels of 43.08 and 7.66 mg kg^{-1} dry mass when MAP was used (Table 2). Similar results were observed for the K and Mg concentrations of cabbage shoots. However, an opposite pattern was observed for the Cr concentration which decreased from 10.70 mg kg^{-1} dry mass at unfertilized control to 9.47 mg kg^{-1} dry mass after SSP application, and finally reached the minimum of 6.78 mg kg^{-1} dry mass when MAP was supplied (Table 2). The SSP fertilization tended to increase the shoot Fe concentration compared with MAP and the unfertilized control (Table 2). There was no obvious variation in the Ca, Zn, Cd, and Cu concentrations when different P sources were used (Table 2).

Soils quality after harvesting the vegetables

The soil pH values slightly changed when different P sources were applied, which ranged from 6.69 to 6.91 on average (Table 3). Soil TP concentration was significantly affected by the P source, and its concentration was higher in P fertilized soil than in the unfertilized control soil (Table 3). The soil TP concentration slightly decreased after MAP application compared to that with SSP fertilization. Similar results were observed for soil Olsen-P concentration. The soil TN and mineral-N concentrations were significantly affected by the P source as well (Table 3). Higher TN and mineral-N concentrations were observed in P-fertilized soil than in the unfertilized control which reached maximum values of 0.96 and 0.18 g kg^{-1}, respectively, when MAP was used. The MAP fertilization significantly increased the Mg accumulation in the soil after harvesting cabbage (Table 3). However, the P source had no significant impact on the concentrations of other metal elements, including Cr, Zn, Cd, Cu, Pb, Fe, Ca, and K, in the soil (Table 3).

Soils solution

The pH values of the soil solution were insignificantly affected by P source, but greatly varied over time during

Table 3. Effects of P source on the pH values and the concentrations of mineral-N, Olsen-P, TN, TP, and metal elements in the soil collected after harvesting vegetables.

Source of variance	pH	Mineral-N	Olsen-P	Cr	Zn	Cd	Cu	Pb	TN	TP	Fe	Ca	K	Mg
	p-values													
P source	*	***	*	ns[†]	ns	ns	ns	ns	***	**	ns	ns	ns	*
		----------------mg/kg----------------							----------------g/kg----------------					
Control	6.83a	73.46b[‡]	38.78b	69.80	69.00	0.91	15.38	27.39	0.91b	0.82b	20.56	4.28	17.84	1.06b
SSP	6.69b	79.17b	44.56a	70.90	71.19	0.84	15.48	26.75	0.92b	0.90a	21.06	4.64	18.14	1.19ab
MAP	6.91a	176.55a	40.59ab	72.54	69.91	0.86	15.09	24.83	0.96a	0.86ab	20.84	4.79	18.56	1.23a

*, **, *** represent the significant level at α=0.05, 0.01, and 0.001, respectively. [†]ns, not significant at α=0.05. [‡]Mean values followed the same letter within a column are not significantly different at α=0.05. The SSP and MAP indicate the SSP and MAP, respectively.

Table 4. Effects of P source and sampling date (days) on the pH values and the concentrations of mineral-N, soluble-P, TN, TP, and metal elements in the soil solution.

Source of variance	pH	TN	Mineral-N	Ca	Soluble-P	Zn	Cu	TP	Fe	K	Mg
	p values										
P source (P)	ns[†]	**	**	*	**	***	ns	***	ns	ns	*
Sampling date (D)	***	***	*	***	***	***	*	***	***	***	***
P * D	ns	ns	ns	ns	**	*	ns	ns	ns	ns	ns
P source		------------- mg/L-------------			------------------------------------- mg/L-------------------------------------						
Control	6.12	0.54c[‡]	0.10c	0.81b	0.93c	0.13b	0.01	1.69c	0.01	24.36	195.01b
SSP	5.95	0.72b	0.16b	1.21a	5.02a	0.17b	0.01	6.40a	0.02	25.57	218.41b
MAP	5.97	0.87a	0.31a	1.00b	4.71a	0.24a	0.01	3.80b	0.01	31.27	387.55a
Sampling date		-------------mg/L-------------			--mg/L------------------------------------						
14	5.72c	0.87a	0.20a	1.27a	5.19a	0.31a	0.02a	5.44a	0.03a	54.24a	362.41a
28	5.86b	0.87a	0.18ab	1.10b	4.51a	0.16b	0.01b	4.86a	0.01b	33.42b	322.93b
42	6.45a	0.43b	0.15b	0.62c	2.73b	0.08b	0.00c	1.82b	0.01b	13.55c	275.63c

*, **, *** represent the significant level at α= 0.05, 0.01, and 0.001, respectively. [†]ns, not significant at α=0.05. [‡]Mean values followed the same letter within a column are not significantly different at α=0.05. The SSP and MAP indicate the SSP and MAP, respectively.

the cabbage growing period which increased from 5.72 at 14 days after planting (DAP) to 6.45 at 42 DAP (Table 4). The P fertilization and sampling date significantly affected the TN and mineral-N concentrations in the soil solution (Table 4). The concentrations of TN and mineral-N were 0.54 and 0.10 mg L^{-1} for unfertilized control, then increased to 0.72 and 0.16 mg L^{-1} for SSP, and finally maximized to 0.87 and 0.31 mg L^{-1} when MAP was used. Both TN and mineral-N concentrations gradually decreased over time during the growing period (Figure 1a and b). The concentrations of TP and soluble-P were also significantly influenced by P source and sampling time (Table 4). The TP concentration significantly decreased over time for SSP treatment, but slightly reduced for the control and MAP (Figure 1d). During the entire growing season, the soluble-P concentration decreased significantly, this was also related to the P source (Figure 1c). For the unfertilized control, the soluble-P concentration progressively decreased from 1.81 at 14 DAP to 0.63 mg L^{-1} at 42 DAP. Compared to the unfertilized control and MAP, the concentration soluble-P in the soil solution decreased more rapidly with SSP as a P source. The P source significantly affected Ca, Zn, and Mg concentrations and insignificant effects were observed for Cu, Fe, and K concentrations in soil solution (Table 4). Obviously higher concentrations of Mg and Zn were observed for MAP fertilization when compared to control and SSP treatments. However, the Ca concentration was maximum when SSP was proposed as P fertilizer compared with control and MAP. For all the metal elements determined in this study, their concentrations gradually decreased from 14 to 42 DAP (Table 2 and Figure 2).

DISCUSSION

Effects of P fertilization on cabbage biomass

In this study, P fertilization significantly promoted cabbage

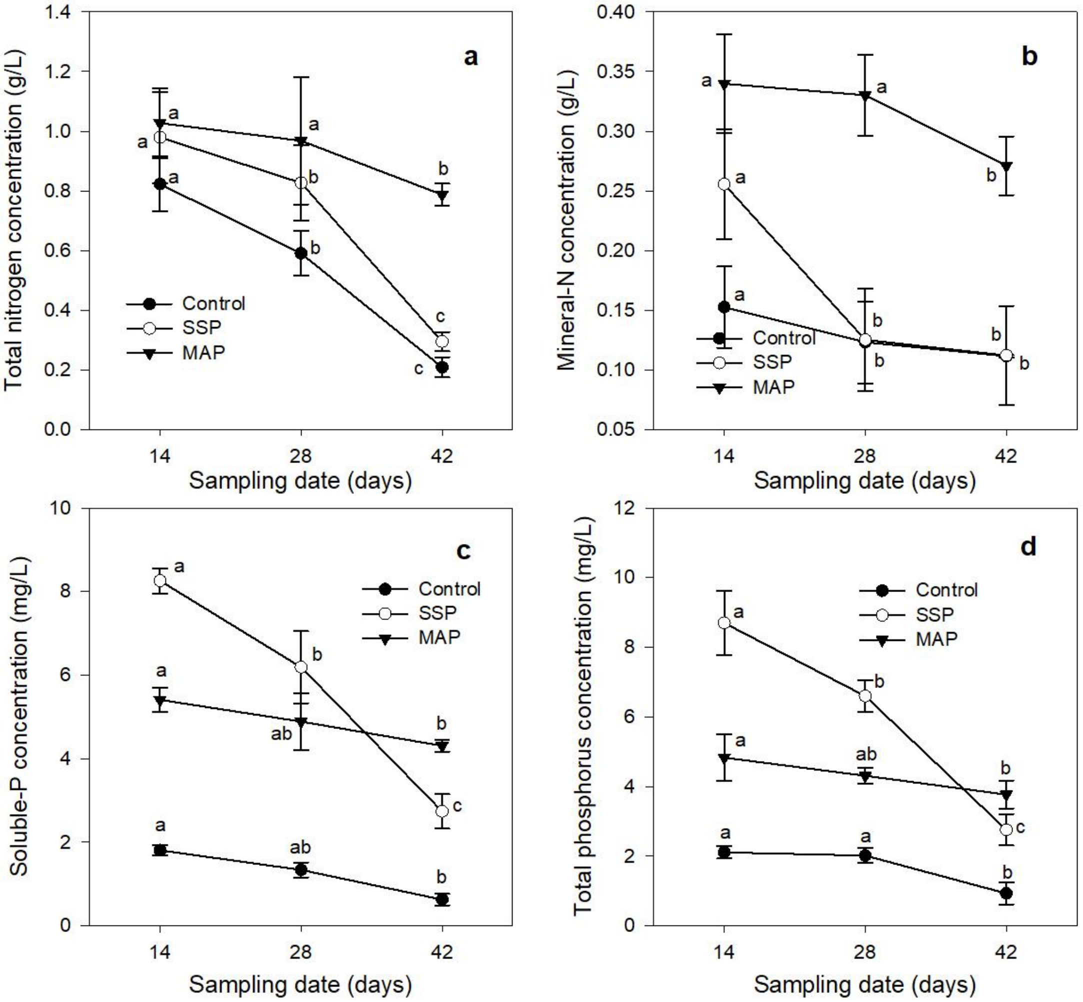

Figure 1. Effects of P source on the concentrations of total N (a), mineral-N (b), soluble-P (c), and total P (d) of soil solutions at different sampling dates. The SSP and MAP indicate the SSP and MAP, respectively.

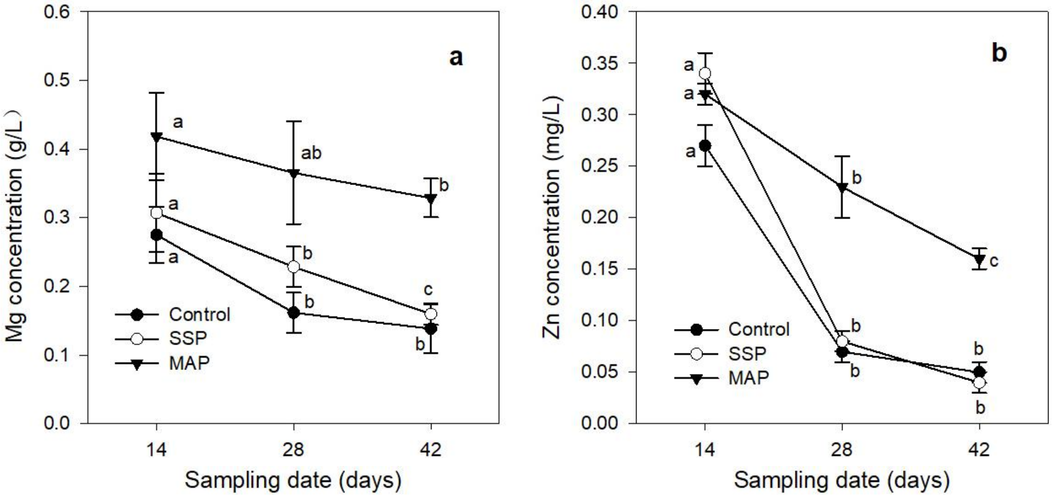

Figure 2. Effects of P source on the concentrations of Mg (a) and Zn (b) of soil solutions at different sampling dates. The SSP and MAP indicate the SSP and MAP, respectively.

Table 5. Pearson correlation coefficients between the dry mass, TN, TP, and metal elements of shoots (n=12).

	Dry mass	TN	Ca	Cr	Cu	Fe	K	Mg	TP	Cd	Zn
Dry mass	1.00										
TN	0.11	1.00									
Ca	0.26	-0.50	1.00								
Cr	-0.43	0.02	0.21	1.00							
Cu	0.55	0.14	0.44	0.11	1.00						
Fe	0.10	0.03	0.46	0.68*	0.42	1.00					
K	0.82*	0.26	0.10	-0.36	0.41	-0.11	1.00				
Mg	0.85*	-0.03	0.80**	-0.01	0.77**	0.42	0.41	1.00			
TP	0.39	-0.07	0.69*	0.12	0.79**	0.48	0.85*	0.88***	1.00		
Cd	0.08	0.13	0.29	0.61	0.47	0.08	-0.05	0.36	0.49	1.00	
Zn	-0.17	0.71**	-0.38	0.24	0.26	0.10	0.27	-0.04	0.11	0.20	1.00

*, **, *** represent the significant level at α= 0.05, 0.01, and 0.001, respectively.

growth (Table 2), which well determined that P is a critical and indispensable element for crop growth and external P fertilization could increase crop yield (Wang and Li, 2004; Kim and Li, 2016). Compared with SSP, MAP fertilization slightly increased the above-ground cabbage shoot biomass (Table 2). Ryu et al. (2012) reported a similar result that MAP could better promote cabbage growth than SSP. In our study, higher amounts of Mg and K were added to the soil when MAP was used than with the SSP application (Table 1), which promoted cabbage shoot growth based on our Pearson correlation analysis (Table 5). Generally, Mg plays an important role in enhancing plant photosynthesis because it is a component of chlorophyll and the activating agent of enzymes (Vafaie et al., 2013; Farhat et al., 2016). The growth-promoting effect of K in vegetables was also supported by González-Ponce et al. (2009). Therefore, an external K and Mg supply is important in promoting cabbage shoot growth.

Effects of P fertilization on vegetable quality

The quality of vegetables is important to human health when they are consumed. There are many limiting factors in vegetable quality, and heavy metal accumulation in shoots is regarded as the most important contaminate to food security (Singh et al., 2016). Oyedele et al. (2006) reported that fertilizer application could potentially increase soil heavy metal accumulation. The average concentrations of Cd and Cr were 0.97 and 6.78 mg kg^{-1} dry mass of the cabbage shoot with MAP fertilization which was within the Chinese food security criterion (GB2762-2017) when the shoot moisture was considered at 97% (Table 2). The Cu concentration in vegetable shoots ranged from 8.36 to 8.79 mg kg^{-1} dry mass, which was within the U.S. national limit of 0.8–18.0 mg kg^{-1} dry mass (Ginocchio et al., 2002). Compared with SSP, MAP fertilization slightly decreased the shoot Cd and Cr concentrations (Table 2), which were identified as potentially hazardous agents to human health even at quite low concentrations (White and Broadley, 2005; Luo et al., 2012). Therefore, MAP seems a safer P fertilizer for cultivating vegetables than SSP.

According to White and Broadley (2005), humans require a considerable quantity of K, Mg, Ca and Fe for the daily activities and low levels of these elements could result in non-premium vegetable quality. In our study, MAP fertilization significantly promoted Mg and K accumulation, with similar Fe, Zn, and Ca contents in the cabbage shoot when compared with SSP (Table 2), which was mainly due to the additional amount of these chemicals along with P fertilization. Therefore, MAP recovered from the mixture of human urine and municipal sewage can be proposed as an effective P fertilizer for obtaining high-quality cabbage.

Effects of P fertilization on soil fertility

Soil nutrients are essential components of soil fertility, which is the most limiting factor in agricultural productivity (Gruhn et al., 2000). Additionally, the soil pH is the basic factor which can partly determine soil fertility because it can influence nutrient release from fertilizers or even from the particulate organic matter in the soil (Liu et al., 2016). In this study, SSP fertilization significantly reduced soil pH levels and no obvious variation in soil pH was observed between MAP fertilization and the unfertilized control (Table 3). Zhalnina et al. (2015) reported that ammonium sulfate is an acidic fertilizer and its application could decrease soil pH through increasing nitrification. Thus, it seems that MAP application increased soil pH, which precisely offset the pH reduction due to ammonium sulfate fertilization. Rahman et al. (2011) also observed that MAP fertilization increased the soil pH which could be well explained during MAP dissolution process with the following chemical reaction:

$$MgNH_4PO_4{\cdot}6H_2O \rightarrow Mg^{2+}+NH_4^{+}+HPO_4^{2-}+OH^{-}+5H_2O$$

Based on these results, we concluded that the combination of MAP and ammonium sulfate was better than that of SSP and ammonium sulfate for soil fertility preservation and for reducing the possibility of soil nutrients lost through leaching or runoff. Additionally, MAP provided more quantity of N (mineral-N and TN) and a comparable level of P (TP and Olsen-P) when compared with SSP fertilization (Table 3). The MAP also provided the soil with a considerable quantity of micronutrients, such as Mg and K, which are essential for promoting plant growth. Besides, the concentrations of all the nutrients and metal elements, such as soluble-P and Mg, were progressing reduced over time during the cabbage cultivation period (Table 4), which determined that MAP is a promising slow-release fertilizer. Therefore, it is concluded that MAP from the mixed wastewater of human urine and municipal sewage is an effective fertilizer with multiple macronutrients and micronutrients to maintain soil fertility with a slow-release property.

Conclusions

In this study, the MAP recovered from the mixed wastewater of human urine and municipal sewage was more effective in promoting Chinese cabbage growth compared to fertilizer SSP because MAP was rich in Mg and K elements. Also, the cabbage fertilized with MAP had better quality than that with SSP in heavy metals, such as Cr and Cd. Finally, MAP application increased the soil fertility as well after cabbage harvesting. Based on these findings, it was concluded that MAP derived from the mixed wastewater of human urine and municipal sewage is an effective, promising, and economic P fertilizer in cultivating vegetables.

ACKNOWLEDGMENTS

We would like to thank Dr. Noura Ziadi from Agriculture and Agri-Food Canada for her help in improving the manuscript language. Financial support for this study was provided by the National Key Research and Development Planof China (2016YFD0800100) and the Key Projects in the National Science and Technology Pillar Program of China (2012BAJ24B06-2B). The lead author acknowledges “Le Fonds de recherche du Québec – Nature et technologies (FRQNT)” for providing him with a Ph.D. scholarship to study at Université Laval.

REFERENCES

Balemi T. & Negisho K. (2012). Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. J. Soil Sci. Plant Nutr. 12(3):547-562. https://doi.org/10.4067/S0718-95162012005000015

Bouain N., Kisko M., Rouached A., Dauzat M., Lacombe B., Belgaroui N., Ghnaya T., Davidian J. C., Berthomieu P., Abdelly C. & Rouached H. (2014). Phosphate/Zinc interaction analysis in two lettuce varieties reveals contrasting effects on biomass, photosynthesis, and dynamics of Pi transport. BioMed. Res. Int. 2014:548254. https://doi.org/10.1155/2014/548254

Cordell D., Drangert J. O. & White S. (2009). The story of phosphorus: Global food security and food for thought. Glob. Environ. Change. 19(2):292-305. https://doi.org/10.1016/j.gloenvcha.2008.10.009

Correll D. L. (1998). The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27(2):261-266. https://doi.org/10.2134/jeq1998.00472425002700020004x

Doyle J. D. & Parsons S. A. (2002). Struvite formation, control and recovery. Water Res. 36(16):3925-3940. https://doi.org/10.1016/S0043-1354(02)00126-4

Farhat N., Elkhouni A., Zorrig W., Smaoui A., Abdelly C. & Rabhi M. (2016). Effects of magnesium deficiency on photosynthesis and carbohydrate partitioning. Acta. Physiol. Plant. 38:145. https://doi.org/10.1007/s11738-016-2165-z

Frossard E., Achat D. L., Bernasconi S. M., Bünemann E. K., Fardeau J. C., Jansa J., Morel C., Rabeharisoa L., Randriamanantsoa L., Sinaj S., Tamburini F. & Oberson A. (2011). The use of tracers to investigate phosphate cycling in soil–plant systems. In: Bünemann, E., Oberson, A., Frossard, E., (eds). Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Springer Berlin Heidelberg, Berlin, Heidelberg. Pp. 59-91.

Ginocchio R., Rodríguez P. H., Badilla-Ohlbaum R., Allen H. E. & Lagos G. E. (2002). Effect of soil copper content and pH on copper uptake of selected vegetables grown under controlled conditions. Environ. Toxicol. Chem. 21(8):1736-1744. https://doi.org/10.1002/etc.5620210828

González-Ponce R., López-de-Sá E. G. & Plaza C. (2009). Lettuce response to phosphorus fertilization with struvite recovered from municipal wastewater. HortScience. 44(2):426-430.

Greaves J., Hobbs P., Chadwick D. & Haygarth P. (1999). Prospects for the recovery of phosphorus from animal manures: A review. Environ. Technol. 20(7):697-708. https://doi.org/10.1080/09593332008616864.

Gruhn P., Goletti F. & Yudelman M. (2000). Integrated nutrient management, soil fertility, and sustainable agriculture: Current issues and future challenges. Food, agriculture, and the environment discussion paper 32, International Food Policy Research Institute, Washington D.C., U.S.A. ISBN 0-89629-628-5.

Kim H. J. & Li X. (2016). Effects of phosphorus on shoot and root growth, partitioning, and phosphorus utilization efficiency in Lantana. HortScience. 51(8):1001-1009.

Kirkby E. A. & Johnston A. E. (2008). Soil and fertilizer phosphorus in relation to crop nutrition. In: White, P.J., Hammond, J.P., (eds). The ecophysiology of plant-phosphorus interactions. Springer Netherlands, Dordrecht. Pp. 177-223.

Larsen T. A. & Gujer W. (1996). Separate management of anthropogenic nutrient solutions (human urine). Water Sci. Technol. 34(3-4):87-94. https://doi.org/10.1016/0273-1223(96)00560-4.

Liu B., Giannis A., Zhang J., Chang V. W. C. & Wang J. Y. (2013). Characterization of induced struvite formation from source-separated urine using seawater and brine as magnesium sources. Chemosphere. 93(11):2738-2747. https://doi.org/10.1016/j.chemosphere.2013.09.025.

Liu X., Tao Y., Wen G., Kong F., Zhang X. & Hu Z. (2016). Influence of soil and irrigation water pH on the availability of phosphorus in struvite derived from urine through a greenhouse pot experiment. J. Agric. Food Chem. 64(17):3324-3329. https://doi.org/10.1021/acs.jafc.6b00021.

Lu R. K. (1999). Analytical methods of soil and agricultural chemistry. China Agricultural Science and Technology Press. Pp. 107-240.

Luo X. S., Ding J., Xu B., Wang Y. J., Li H. B. & Yu S. (2012). Incorporating bioaccessibility into human health risk assessments of heavy metals in urban park soils. Sci. Total Environ. 424:88-96. https://doi.org/10.1016/j.scitotenv.2012.02.053.

Maynard D. G. & Kalra Y. P. (1993). Nitrate and exchangeable ammonium nitrogen. In: Carter, M.R., (ed). Soil sampling and methods of analysis. Canadian Society of Soil Science, CRC Press, New York, U.S.A. Pp. 25-38.

Mehta C. M., Hunter M. N., Leong G. & Batstone D. J. (2018). The value of wastewater derived struvite as a source of phosphorus fertilizer. Clean - Soil, Air, Water. 46(7):1700027.

Mihelcic J. R., Fry L. M. & Shaw R. (2011). Global potential of phosphorus recovery from human urine and feces. Chemosphere. 84(6):832-839. https://doi.org/ 10.1016/j.chemosphere.2011.02.046

Nkonge C. & Balance G. M. (1982). A sensitive colorimetric procedure for nitrogen determination in micro-Kjeldahl digests. J. Agric. Food Chem. 30(3):416-420. https://doi.org/10.1021/jf00111a002

Oyedele D. J., Asonugho C. & Awotoye O. O. (2006). Heavy metals in soil and accumulation by edible vegetables after phosphate fertilizer application. Electron. J. Environ. Agric. Food Chem. 5(4):1446-1453.

Rahman M. M., Liu Y., Kwag J. H. & Ra C. (2011). Recovery of struvite from animal wastewater and its nutrient leaching loss in soil. J. Hazard Mater. 186(2–3):2026-2030. https://doi.org/10.1016/j.jhazmat.2010.12.103.

Rahman M. M., Salleh M. A. M., Rashid U., Ahsan A., Hossain M. M. & Ra C. S. (2014). Production of slow release crystal fertilizer from wastewaters through struvite crystallization – A review. Arab. J. Chem. 7(1):139-155. https://doi.org/10.1016/j.arabjc.2013.10.007.

Ryu H. D., Lim C. S., Kang M. K. & Lee S. I. (2012). Evaluation of struvite obtained from semiconductor wastewater as a fertilizer in cultivating Chinese cabbage. J. Hazard Mater. 221(222):248-255.

Schroeder J. I., Delhaize E., Frommer W. B., Guerinot M. L., Harrison M. J., Herrera-Estrella L., Horie T., Kochian L. V., Munns R., Nishizawa N. K., Tsay Y. F. & Sanders D. (2013). Using membrane transporters to improve crops for sustainable food production. Nature. 497:60-66. https://doi.org/10.1038/nature11909.

Schroeder P. D., Radcliffe D. E. & Cabrera M. L. (2004). Rainfall timing and poultry litter application rate effects on phosphorus loss in surface runoff. J. Environ. Qual. 33(6):2201-2209. https://doi.org/10.2134/jeq2004.2201.

Singh S., Parihar P., Singh R., Singh V. P. & Prasad S. M. (2016). Heavy metal tolerance in plants: Role of transcriptomics, proteomics, metabolomics, and ionomics. Front Plant Sci. 6:1143. https://doi.org/10.3389/fpls.2015.01143.

Stratful I., Scrimshaw M. D. & Lester J. N. (2001). Conditions influencing the precipitation of magnesium ammonium phosphate. Water Res. 35(17):4191-4199. https://doi.org/10.1016/S0043-1354(01)00143-9.

Uysal A. & Kuru B. (2015). The fertilizer effect of struvite recovered from dairy industry wastewater on the growth and nutrition of maize plant. Fresen. Environ. Bull. 24:3155-3162.

Uysal A., Demir S., Sayilgan E., Eraslan F. & Kucukyumuk Z. (2014). Optimization of struvite fertilizer formation from baker's yeast wastewater: Growth and nutrition of maize and tomato plants. Environ. Sci. Pollut. R. 21:3264-3274.

Vafaie A., Ebadi A., Rastgou B. & Moghadam S. H. (2013). The effects of potassium and magnesium on yield and some physiological traits of Safflower (*Carthamus tinctorius*). Int. J. Agric. Crop Sci. 5(17):1895-1900.

Wang Z. & Li S. (2004). Effects of nitrogen and phosphorus fertilization on plant growth and nitrate accumulation in vegetables. J. Plant Nutr. 27(3):539-556. https://doi.org/10.1081/PLN-120028877.

Wen G., Hu Z., Liu X. & Huang L. (2018). Improvement of the quality of struvite crystals recovered from a mixture of human urine and municipal sewage via a novel two-step precipitation method. Environ. Technol. Innov. 12:80-90. https://doi.org/10.1016/j.eti.2018.08.003.

White P. J. & Broadley M. R. (2005). Biofortifying crops with essential mineral elements. Trends Plant Sci. 10(12):586-593.

Zhalnina K., Dias R., de Quadros P. D., Davis-Richardson A., Camargo F. A., Clark I. M., McGrath S. P., Hirsch P. R. & Triplett E. W. (2015). Soil pH determines microbial diversity and composition in the park grass experiment. Microb. Ecol. 69(2):395-406. https://doi.org/10.1007/s00248-014-0530-2.