SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage: www.akademiabaru.com/araset.html
ISSN: 2462-1943

Investigation on the Effect of Nickel and Cadmium on Struvite Crystallization in Landfill Leachate

Mohamad Darwish[1,*], Shaymaa Mustafa[2], Nur Zulaikha Yaakub[1], Fahid K. J. Rabah[3]

[1] Department of Water and Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia.
[2] Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia.
[3] Faculty of Environmental Engineering, The Islamic University of Gaza, Palestine

ABSTRACT

Struvite is an eco-friendly fertilizer that is widely produced from waste streams. Landfill leachate is rich in ammonium-nitrogen (NH_4-N), which encourages its recovery in the form of struvite, however, the presence of heavy metals, especially Cd and Ni, could affect the purity of struvite crystals. This work aimed at studying the effect of Cd and Ni on the purity and morphology of struvite crystals obtained from synthetic solution (Phase 1) and synthetic landfill leachate (Phase 2). Batch experiments of struvite precipitation were implemented with different concentrations of Cd and Ni. The results of aqueous analysis showed minor reduction in NH_4-N recovery in both phases when Cd or Ni existed. Moreover, XRD and SEM analyses of solid samples illustrated that all crystals were highly pure struvite. In addition, the effect of Cd and Ni in Phase 2 was slightly more significant than in Phase 1. The results suggested that struvite can be safely recovered from landfill leachate contaminated with Cd and Ni, however, more intense research should be conducted on actual landfill leachate to have deeper understanding of mutual and advanced effects of heavy metals.

Keywords:

Struvite; landfill leachate; cadmium; nickel; ammonium-nitrogen

1. Introduction

Landfills pose serious threat to the environment due to the hazardous leachates produced. Landfill leachate is a result of complicated chemical reactions within the solid wastes components, which make it highly concentrated in ammonium nitrogen (NH4-N), organic content and some heavy metals [1]. Several techniques were introduced for the treatment of landfill leachate, such as activated carbon [2], ammonia stripping [3] and chemical precipitation [4]. On the other hand, the sustainable practice of solid waste management promotes the recovery of valuable products from leachate like food waste composting [5,6], biogas [7] and organic fertilizers [8]. In general, recycling practice promotes environmental conservation, limits pollution, and contributes to circular economy benefits [9-11].

* *Corresponding author.*
E-mail address: sjmohamad@utm.my

https://doi.org/10.37934/araset.64.1.1322

The process of precipitation of ammonium nitrogen (NH_4-N) forming magnesium ammonium phosphate ($MgNH_4PO_4.6H_2O$), known as Struvite, has been deeply studied since 18th century. Struvite crystallization technology was developed as a phenomenal process for the purpose of phosphate and nitrogen recovery [12], since it can be applied to a wide range of wastewaters containing nitrogen in the form of NH_4-N [13]. The major advantage of this technique is the recovery of NH4-N in the form of struvite; a slow-release fertilizer that is environmentally friendly and safe for plants and soil [14]. Furthermore, struvite crystallization process contributes significantly to the circular economy concept of wastewater treatment plants, via recovery of phosphate from specific units in the plant, such as digester recirculation pumps and activated sludge storage tanks [15].

Wastewater often comprises different kinds of components, such as organic material and heavy metals, which may interfere with struvite precipitation. This is considered a significant threat to the purity of the formed struvite, which could hinder the application of struvite as a fertilizer [16]. According to Huang *et al.,* [17], heavy metals accumulation in struvite increases linearly with their original concentrations in the wastewater. In addition, heavy metals co-precipitation may affect the formation, content, morphology, and surface chemistry of struvite precipitates [18]. Moreover, struvite contaminated with heavy metals may possess negative impact on plants. A recent study has shown that the plant's capability to translocate heavy metals from landfill leachate into the plant tissue is very alarming [19]. The effect of a number of heavy metals on struvite crystallization, such as copper (Cu) and zinc (Zn) [20], chromium (Cr) [21] and arsenic (As) [22], has been widely studied. However, to the best of the authors' knowledge, the effect of Ni and Cd on struvite crystallization was not investigated before, although they are highly concentrated in different types of wastewaters, especially landfill leachate [23, 24].

Landfill leachate is the waste stream generated from municipal or industrial landfills, which contains extremely high concentrations of NH_4-N (exceeding 1,000 mg/L), as well as other pollutants [25, 26]. This encourages the recovery of NH_4-N in the form of struvite. However, the presence of heavy metals could be a threat to the purity of struvite, which might hinder its further application in agronomic field. Therefore, this study aimed to investigate the effect of Ni and Cd on struvite crystals obtained from landfill leachate.

2. Methodology

This study consists of 2 experimental phases. In Phase 1, a synthetic solution of ammonium chloride (NH_4Cl) was used for struvite crystallization, while in Phase 2, synthetic landfill leachate was used with the same concentration of struvite components and heavy metals as Phase 1. All used reagents were of analytical grade.

2.1 Phase 1: Struvite Crystallization Using Synthetic Solution

The synthetic solution of 0.07M NH_4Cl was prepared representing the normal range of NH_4-N in landfill leachate (around 990mg/L). Equimolar ratio of all struvite components (i.e., Mg, N and P) was implied in this study, hence the same molar value was used for PO_4 and Mg. Due to its high solubility in water, magnesium sulphate heptahydrate ($MgSO_4.7H_2O$) was used as the Mg source, while sodium dihydrogen phosphate (NaH_2SO_4) was used as the source of PO_4. All stock solutions were prepared using deionized water and the same stock solutions were used throughout the study to obtain uniform and precise results. With regards to heavy metals contamination, certain amount of Ni and Cd solutions were spiked into the synthetic solution as shown in Table 1. For Ni and Cd sources, nickel (II) chloride hexahydrate ($NiCl.6H_2O$) and cadmium chloride hemi pentahydrate ($CdCl.2½H_2O$) were applied, respectively. The concentration ranges of Cd and Ni were chosen based on the rates commonly found in actual landfill leachates [27,28].

Struvite precipitation normally occurs at pH values range from 7.0 to 9.50 [13]. A pH value of around 8.0 was chosen for the experiments of Phase 1 and 2, according to the results obtained by Li *et al.,* [29]. The initial pH was adjusted using 1.0M sodium hydroxide (NaOH) solution until the pH is 8.0±0.05, before the reaction solution was stirred for 30 min using magnetic stirrer. Consequently, the sample was left to settle down for 1 hr. Liquid samples were collected using 0.45 µm syringe filters for further analyses, whereas the remaining solution was filtered using vacuum filter, then washed twice with deionized water before drying for 24 hours in room temperature. Finally, the solid samples were collected for further analysis.

Table 1
Concentrations of Ni and Cd in Phase 1 and Phase 2

Heavy metals	Molar concentration (µ mol/L)
Ni	8.54
	38.87
	58.10
Cd	4.38
	21.90
	43.79

2.2 Phase 2: Struvite Crystallization Using Synthetic Landfill Leachate

The same experiment was repeated for Phase 2, with the replacement of synthetic solution by synthetic landfill leachate. The study of Rowe *et al.,* [30] structured a detailed recipe of synthetic landfill leachate that includes precise concentrations of organic matter (suspended and dissolved), ammoniacal nitrogen, phosphate and trace metals. The recipe was similar to a real leachate collected through a period of 3 months. The current study adapted the recipe of Rowe *et al.,* [30] with some modification of trace metals concentrations and NH_4-N content, as presented in Table 2. The same molar concentrations of Mg, NH_4 and PO_4, as well as concentrations of Ni and Cd, applied in Phase 1 were used during the preparation of synthetic landfill leachate in Phase 2.

Table 2
Composition of synthetic landfill leachate (Adapted from Rowe *et al.,* [30])

Component	Per 1 L
Acetic acid (100%)	5 mL
Propionic acid (100%)	1 mL
Butyric acid (100%)	1 mL
$MgSO_4.7H_2O$	17.253 g
Na_2CO_3	0.120 g
$Ca(NO_3)_2$	0.100 g
NH_4Cl	3.744 g
NaH_2SO_4	8.398 g

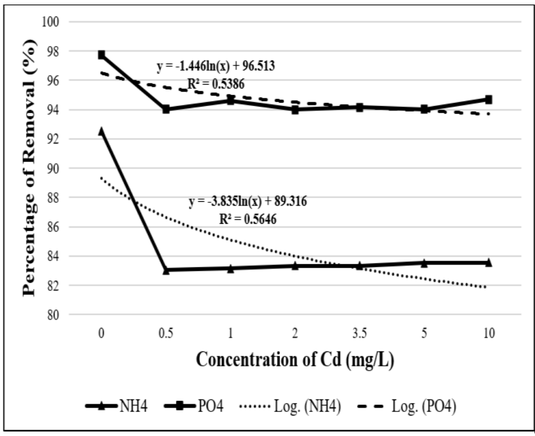
2.3 Analysis of samples

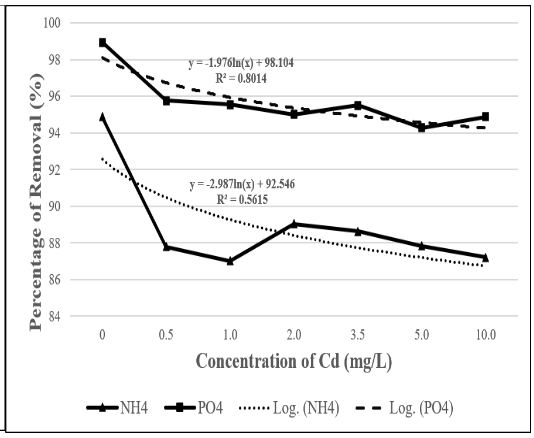
The concentration of NH_4-N in liquid samples was measured using Nessler's standard method, while PO_4 was measured using spectrophotometry analysis (HACH DR6000). Atomic adsorption spectrophotometry (AAS, 3300, Perkin Elmer, USA) was used to analyse the concentrations of Ni and Cd in liquid samples. Solid samples of struvite precipitates were analysed using X-ray diffraction (XRD, Rigaku Americas Corporation, The Woodlands, TX) and Scanning Electron Microscopy (SEM, Gemini, Zeiss Supra Series, Germany).

3. Results

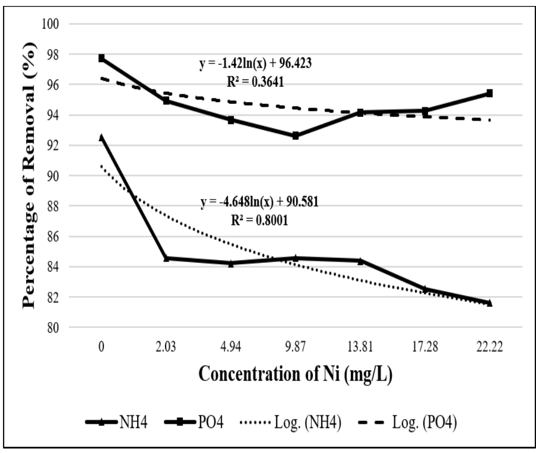
3.1 Removal of NH_4-N and PO_4 in the presence of Cd and Ni

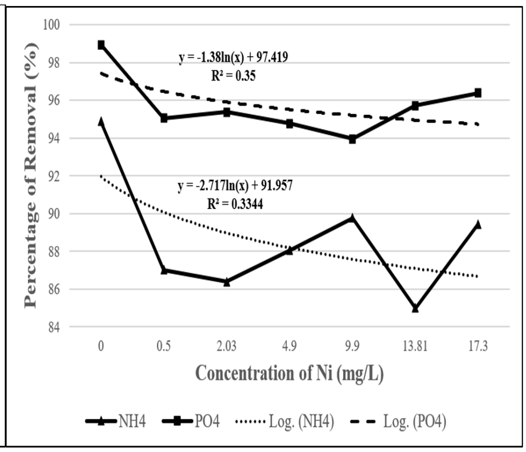
Figure 1(a) – Figure 1(d) shows the removal percentage of NH_4-N and PO_4 when interacting with Cd and Ni. For Phase 1, as illustrated in Figure 1(a) and (c), the removal percentage for both NH_4-N and PO_4 was 92.56% and 97.74%, respectively. Meanwhile, for Phase 2, as illustrated in Figure 1(b) and (d), the removal percentages witnessed a minute change; removal of NH_4-N and PO_4 was 94.88% and 98.93%, respectively. The results are consistent with previous studies. Huang *et al.,* [31] achieved 92% removal of NH_4-N, and Miroslav *et al.,* [22] achieved 96% removal of PO_4 in wastewater by struvite crystallization.





(a) Phase 1 with Cd (b) Phase 2 with Cd





(c) Phase 1 with Ni (d) Phase 2 with Ni

Fig. 1. Removal of NH_4-N and PO_4 in Phase 1 (a) & (c) and Phase 2 (b) & (d)

Referring to Figure 1 (a) and (b), based on the trendlines, the percentage of NH_4-N removal reduced as the initial Cd concentration increased. However, the reduction NH_4-N removal in Phase 1 was more significant than Phase 2. While for PO_4 removal, no significant changes were noticed since the curve of the plotted trendline fairly shows a straight line when the initial concentration of Cd increases from 0.5mg/L to 10mg/L. Figure 1(c) and Figure 1(d) show the removal of NH_4-N and PO_4 when interact with Ni. Based on the trendlines, percentage of NH_4-N removal reduced as the initial Ni concentration increased. Similar to the interaction with Cd, there were no significant changes for the removal for PO_4. On the other hand, some fluctuations in NH_4-N removal were noticed (Figure 1 (d)), probably due to the interaction between the components in synthetic landfill leachate solution during the reaction. A study performed by Muhmood *et al.,* [32] shows that the removal percentage of Ni by struvite precipitation from poultry wastewater was 16.4% with significant amount of Ni in the final struvite precipitates.

3.2 Investigation of precipitates morphology and composition

To verify the effect of Cd and Ni on struvite crystals' morphology, XRD analysis was conducted on solid precipitates. The results obtained for all solid samples showed high matching with struvite XRD pattern (Figure 2(a) and Figure 2(b)) and all the solid samples were in crystal form. However, the green pattern in the results displayed some background noise that could be due to amorphous compounds associated with the heavy metals ions of Ni^{2+} and Cd^{2+}. Since the amorphous matter can be detected in XRD analysis, it can be said that the precipitates are in crystal form.

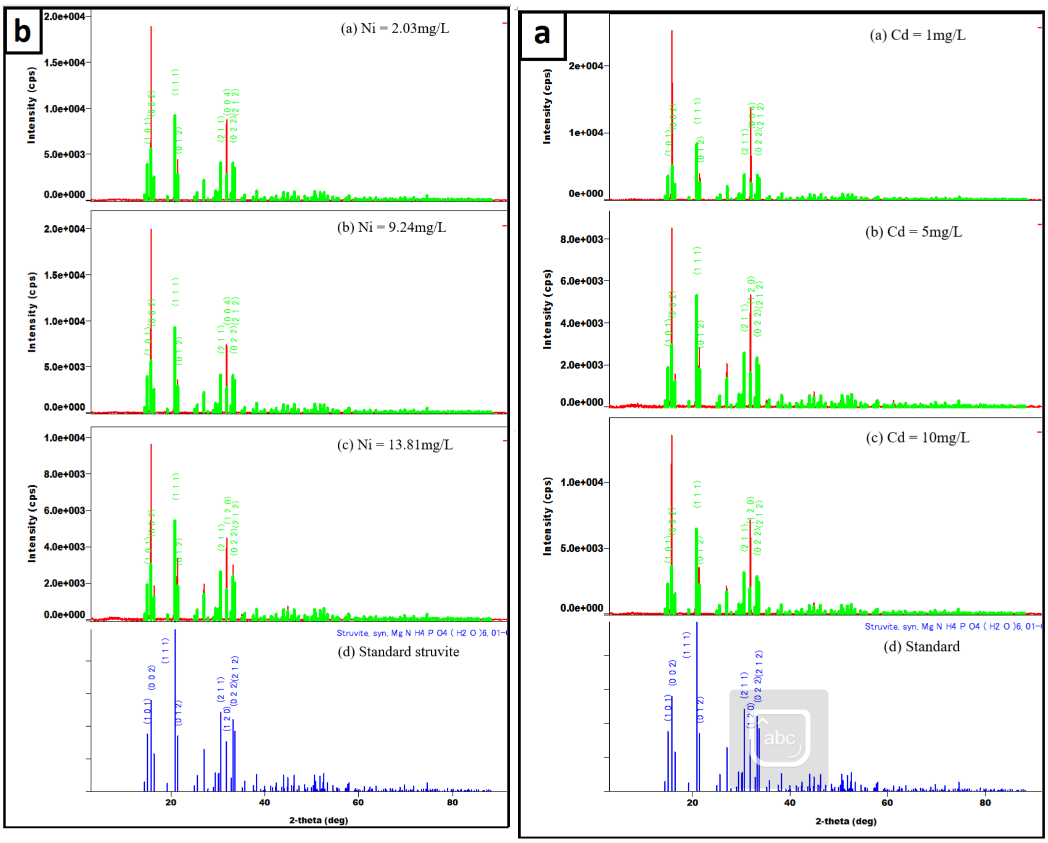
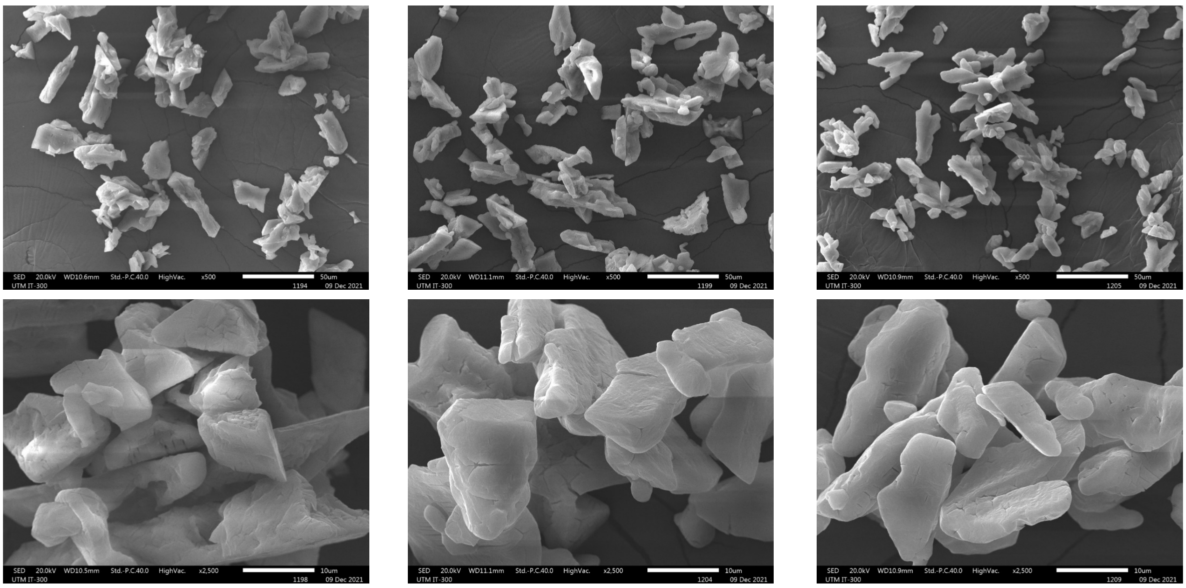


Fig. 2. XRD analysis of solid samples from Phase (1) in the presence of (a) Cd and (b) Ni

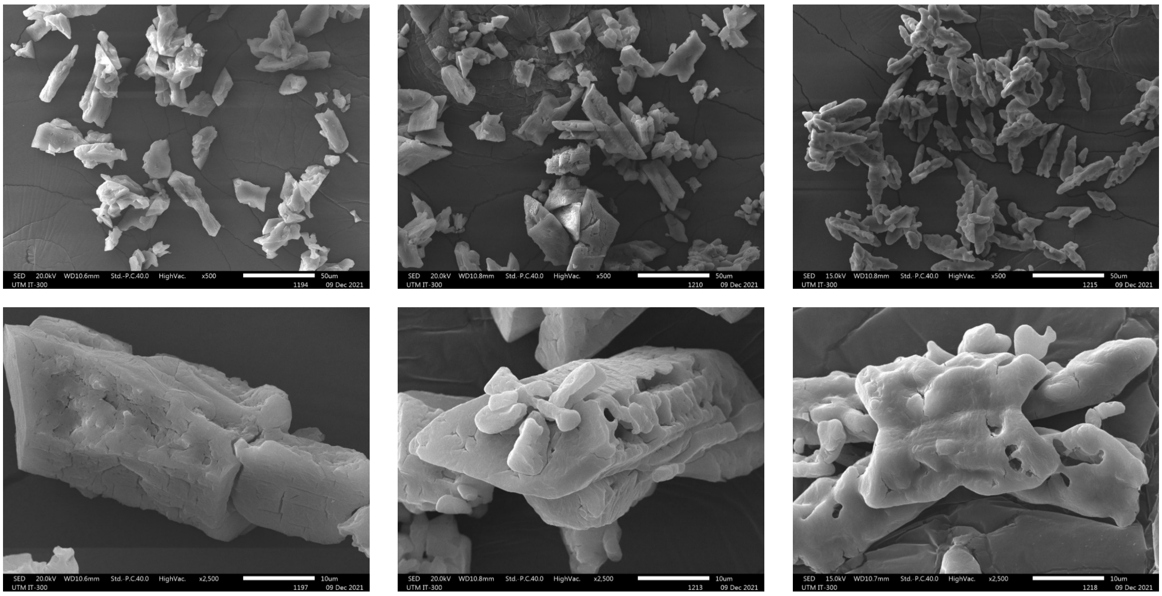
Struvite precipitates were further characterized by SEM analysis, for struvite obtained from the lowest and highest concentrations of Cd and Ni in Phase 1 and Phase 2, alongside with uncontaminated sample. Figure 3 – Figure 6 show the SEM images for the selected precipitates. In general, some differences were noticed between blanks obtained from Phase 1 and Phase 2; SEM images of blank from Phase 2 has obvious crested surface, numerous gullies, and the shape is more prismatic than the blank obtained from Phase 1. This might be due to the difference in the composition of reactions solutions in both phases (i.e. synthetic solution and synthetic landfill leachate), in which the solution in Phase 2 contains organic acids that might have caused such difference. The observation is consistent with a previous study conducted by Tang *et al.,* [33], who used synthetic solution to produce struvite crystals.

Figure 3 and Figure 4 show the effect of Cd and Ni on struvite crystals' shape in Phase 1. It is illustrated that low Cd concentrations did not impose significant changes in the shape and surface of struvite crystals. Even at higher concentrations of Cd (10 mg/L), only a quite smoother surface was observed, which means that Cd did not affect the morphology of struvite when using the synthetic solution. This is consistent with the earlier results of spectrometry analysis of struvite contaminated with Cd. With regards to Ni, it showed clear holes on the surface of crystals, regardless of the low or high concentrations of Ni. This indicates that Ni has a more significant effect on the shape and morphology of struvite. On the opposite side, Cd and Ni in Phase 2 showed more obvious effect on struvite crystals. According to Figure 5 and Figure 6, X-shaped struvite crystals with blunt and round edges were formed (with Cd) and several holes were also noticed on the surface (with Ni), which was consistent with previous results obtained by Manzoor *et al.,* [34] and Kemacheevakul *et al.,* [35]. This means that the effect of Cd and Ni was slightly enhanced in the synthetic landfill leachate, probably due to an interaction with organic acids and other pollutants presented in the solution. Generally, based on the later discussion, struvite can be recovered safely in waste streams contaminated with Cd and Ni (within the examined ranges). This highlights the importance of conducting advanced researches in future to investigate the behavior and effect of heavy metals on struvite crystallization in actual waste streams.



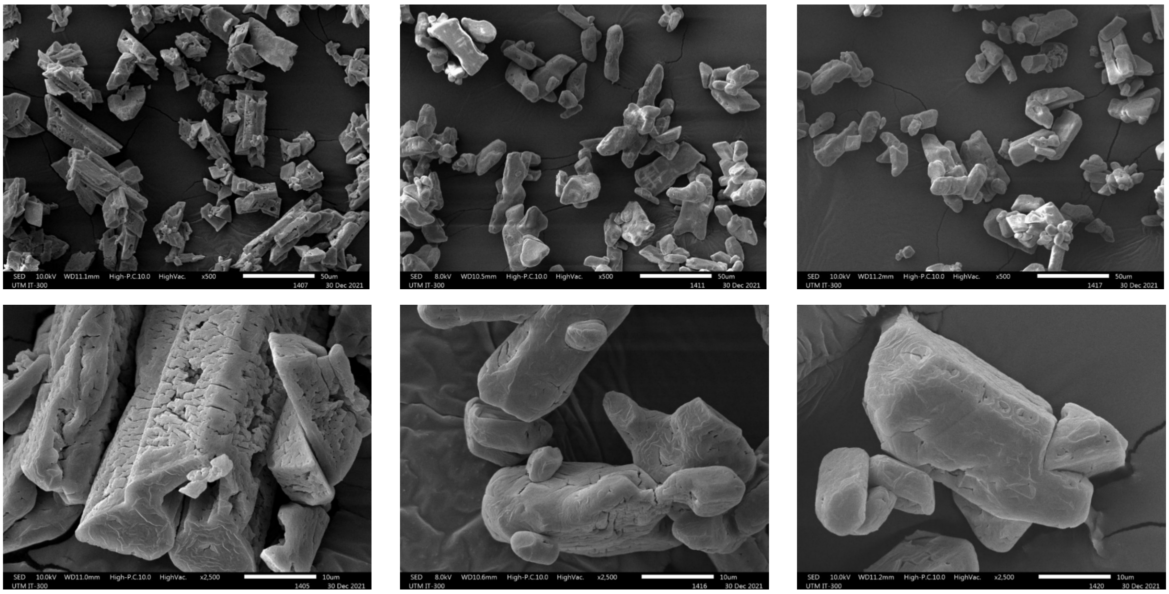
Blank (Phase 1) Cd = 1mg/L Cd = 10mg/L

Fig. 3. SEM images of struvite from blank and Cd contaminated solution (Phase 1)



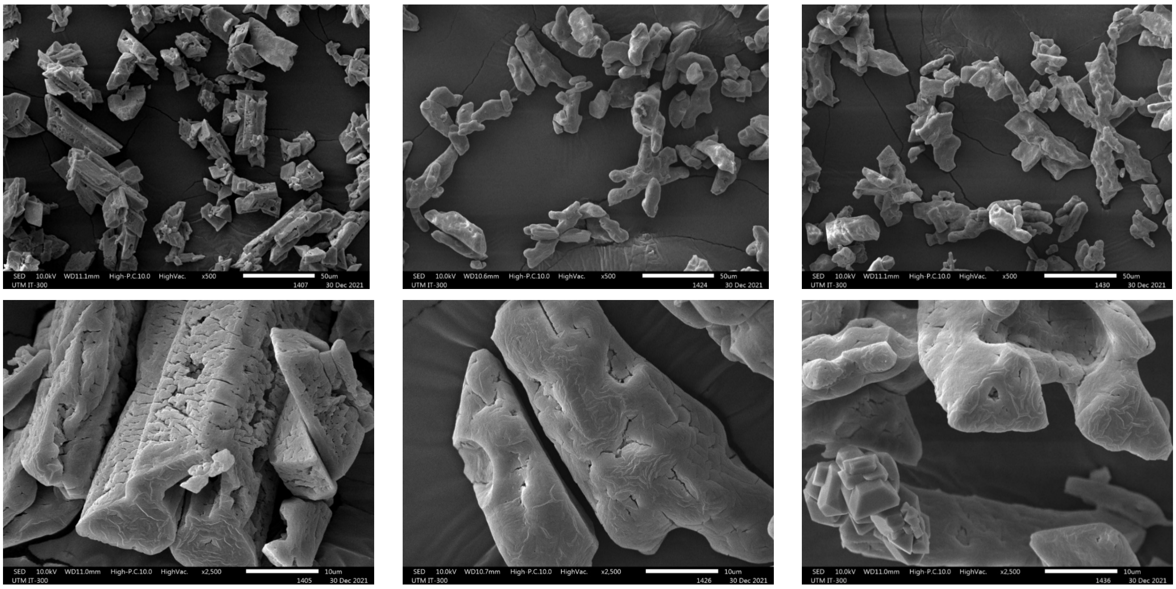
Blank (Phase 1) Ni = 2.03mg/L Ni = 13.81mg/L

Fig. 4. SEM images of struvite from blank and Ni contaminated solution (Phase 1)



Blank (Phase 2) Cd = 0.5mg/L Cd = 5mg/L

Fig. 5. SEM images of struvite from blank and Cd contaminated solution (Phase 2)



Blank (Phase 2) Ni = 0.5mg/L Ni = 13.81mg/L

Fig. 6. SEM images of struvite from blank and Ni contaminated solution (Phase 2)

4. Conclusions

The recovery of NH_4-N from waste streams in the form of struvite is widely applied for several types of wastewaters, such as landfill leachate. However, heavy metals in landfill leachate could restrict the use of the obtained struvite, as it could attach to struvite crystals. The results of this study illustrated that Cd and Ni have minor effect on the purity and morphology of struvite, which was verified by AAS, XRD and SEM analyses. In conclusion, although the effect of Cd and Ni was insignificant, further studies have to be implemented to explore the effect of heavy metals on struvite in actual waste streams.

Acknowledgement
This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS Grant R.J130000.7822.5F632).

References
[1] Darwish, Mohamad, Shaymaa Mustafa, Azmi Aris, Aeslina Abdul Kadir, and Mohamed Zuhaili Mohamed Najib. "Struvite Crystallization: An Effective Technology for Nitrogen Recovery in Landfill Leachate." *Prospects of Fresh Market Wastes Management in Developing Countries* (2020): 143-166. https://doi.org/10.1007/978-3-030-42641-5_9

[2] Yong, Jiunn Boon, Lian See Tan, and Jully Tan. "Comparative life cycle assessment of biomass-based and coal-based activated carbon production." *Progress in Energy and Environment* (2022): 1-15. https://doi.org/10.37934/progee.20.1.115

[3] Trinh, Viet M., Thao Phuong Nguyen, Tung Huu Pham, Hieu Minh Trinh, Minh Tuan Nguyen, Manh Van Do, Long Thanh Ngo, and Tuyen Van Trinh. "Intensified ammonia stripping from landfill leachate using a high-performance rotating reactor." *Journal of Environmental Chemical Engineering* 11, no. 5 (2023): 110416. https://doi.org/10.1016/j.jece.2023.110416

[4] Warmadewanthi, I. D. A. A., Muhammad Agung Zulkarnain, Nurani Ikhlas, Setyo Budi Kurniawan, and Siti Rozaimah Sheikh Abdullah. "Struvite precipitation as pretreatment method of mature landfill leachate." *Bioresource Technology Reports* 15 (2021): 100792. https://doi.org/10.1016/j.biteb.2021.100792

[5] Abu, R., Muhammad Arif Ab Aziz, and Zainura Zainon Noor. "Integrated Life Cycle Assessment, Life Cycle Costing and Multi Criteria Decision Making for Food Waste Composting Management." *Journal of Advanced Research in Technology and Innovation Management* 2, no. 1 (2022): 1-12. https://doi.org/10.37934/arbms.21.1.19

[6] Raimi, Halimatus Sa'adiah Mohamed, Nafratiti Najiha Azlan Shahrul, Tuan Noor Hasanah Tuan Ismail, Roslinda Ali, Riffat Shaheed, and Fatimah Mohamed Yusop. "The Influence of Compost Bin Volume and Effective Microorganisms (EM) Quantity for Efficient Food Waste Composting." *Journal of Advanced Research in Micro and Nano Engineering* 16, no. 1 (2024): 70-84. https://doi.org/10.37934/armne.16.1.7084

[7] Kjerstadius, Hamse, Salar Haghighatafshar, and Åsa Davidsson. "Potential for nutrient recovery and biogas production from blackwater, food waste and greywater in urban source control systems." *Environmental technology* 36, no. 13 (2015): 1707-1720. https://doi.org/10.1080/09593330.2015.1007089

[8] Darwish, M., M. H. Puteh, A. Aris, and A. Abdul Kadir. "Utilisation of fish waste bones ash for struvite precipitation in actual landfill leachate." *International Journal of Environment and Waste Management* 28, no. 2 (2021): 209-218. http://doi.org/10.1504/IJEWM.2021.117193

[9] Rosdi, Nur NadhirahHafawati, Mohamed Syazwan Osman, Huzairy Hassan, Norain Isa, Grzegorz Lisak, and Lili Liang. "Advancement in photocatalyst and piezophotocatalyst micromotor for environmental remediation: a concise review." *Journal of Advanced Research in Micro and Nano Engineering* 22, no. 1 (2024): 116-125. https://doi.org/10.37934/armne.22.1.116125

[10] Isa, N. F., MF Mohammad Zaki, L. Ahmad Sofri, M. Abdul Rahim, Z. Md Ghazaly, and N. Bidin. "The use of rubber manufacturing waste as concrete additive." *Advanced Research in Applied Mechanics* 4, no. 1 (2014): 12-18. https://doi.org/10.1177/0734242X07067448

[11] Adin, Khaled Sharaf, Sharafaddin Saleh, and Bilkis Zabara. "The Quality of Stormwater in Sana'a City from the Perspective of Integrated Water Resources Management." *Journal of Advanced Research in Technology and Innovation Management* 3, no. 1 (2022): 1-10. https://doi.org/10.4296/cwrj2102165

[12] Yetilmezsoy, Kaan, Emel Kocak, Havva Melda Akbin, and Didem Özçimen. "Utilization of struvite recovered from high-strength ammonium-containing simulated wastewater as slow-release fertilizer and fire-retardant barrier." *Environmental technology* 41, no. 2 (2020): 153-170. https://doi.org/10.1080/09593330.2018.1491642

[13] Darwish, Mohamad, Azmi Aris, Mohd Hafiz Puteh, Muzaffar Zainal Abideen, and Mohd Nor Othman. "Ammonium-nitrogen recovery from wastewater by struvite crystallization technology." *Separation & Purification Reviews* 45, no. 4 (2016): 261-274. https://doi.org/10.1080/15422119.2015.1119699

[14] Beckinghausen, Aubrey, Monica Odlare, Eva Thorin, and Sebastian Schwede. "From removal to recovery: An evaluation of nitrogen recovery techniques from wastewater." *Applied Energy* 263 (2020): 114616. https://doi.org/10.1016/j.apenergy.2020.114616

[15] Achilleos, Panayiotis, K. R. Roberts, and I. D. Williams. "Struvite precipitation within wastewater treatment: A problem or a circular economy opportunity?." *Heliyon* 8, no. 7 (2022). https://doi.org/10.1016/j.heliyon.2022.e09862

[16] Li, Bing, Haiming Huang, Zhitao Sun, Ning Zhao, Tajammal Munir, Wei Yu, and Brent Young. "Minimizing heavy metals in recovered struvite from swine wastewater after anaerobic biochemical treatment: Reaction mechanisms and pilot test." *Journal of Cleaner Production* 272 (2020): 122649. https://doi.org/10.1016/j.jclepro.2020.122649

[17] Huang, Haiming, Bing Li, Jing Li, Peng Zhang, Wei Yu, Ning Zhao, Guojun Guo, and Brent Young. "Influence of process parameters on the heavy metal (Zn2+, Cu2+ and Cr3+) content of struvite obtained from synthetic swine wastewater." *Environmental pollution* 245 (2019): 658-665. https://doi.org/10.1016/j.envpol.2018.11.046

[18] Bai, Wenjing, Rui Tang, Guangxue Wu, Wei Wang, Shoujun Yuan, Liwen Xiao, Xinmin Zhan, and Zhen-Hu Hu. "Co-precipitation of heavy metals with struvite from digested swine wastewater: Role of suspended solids." *Journal of Hazardous Materials* 455 (2023): 131633. https://doi.org/10.1016/j.jhazmat.2023.131633

[19] de Oliveira Mesquita, Francisco, Talita Dantas Pedrosa, Rafael Oliveira Batista, and Eunice Maia de Andrade. "Translocation factor of heavy metals by elephant grass grown with varying concentrations of landfill leachate." *Environmental Science and Pollution Research* 28, no. 32 (2021): 43831-43841. https://doi.org/10.1007/s11356-021-13765-1

[20] Hutnik, Nina, Anna Stanclik, Krzysztof Piotrowski, and Andrzej Matynia. "Effect of Copper and Zinc Ions on Struvite Nucleation and Crystal Growth Kinetics in Various Process Environments." *Polish Journal of Environmental Studies* 29, no. 3 (2020). https://doi.org/10.15244/pjoes/110932

[21] Rouff, Ashaki A. "Sorption of chromium with struvite during phosphorus recovery." *Environmental science & technology* 46, no. 22 (2012): 12493-12501. https://doi.org/10.1021/es302296m

[22] Miroslav, Horak, Hic Pavel, Balik Josef, and Koziskova Jarmila. "Arsenic as a contaminant of struvite when recovering phosphorus from phosphogypsum wastewater." *Journal of the Taiwan Institute of Chemical Engineers* 129 (2021): 91-96. https://doi.org/10.1016/j.jtice.2021.10.005

[23] Torres-González, Omar Ricardo, Ivan Moisés Sánchez-Hernández, Mario Eduardo Flores-Soto, Verónica Chaparro-Huerta, Cesar Soria-Fregozo, Laura Hernández-García, Eduardo Padilla-Camberos, and José Miguel Flores-Fernández. "Landfill leachate from an urban solid waste storage system produces genotoxicity and cytotoxicity in

pre-adolescent and Young Adults Rats." *International Journal of Environmental Research and Public Health* 18, no. 21 (2021): 11029. https://doi.org/10.3390/ijerph182111029

[24] Wdowczyk, Aleksandra, and Agata Szymańska-Pulikowska. "Differences in the composition of leachate from active and non-operational municipal waste landfills in Poland." *Water* 12, no. 11 (2020): 3129. https://doi.org/10.3390/w12113129

[25] Anqi, Tu, Zhiyong Zhang, Hao Suhua, and Li Xia. "Review on landfill leachate treatment methods." In *IOP Conference Series: Earth and Environmental Science*, vol. 565, no. 1, p. 012038. IOP Publishing, 2020. https://doi.org/10.1088/1755-1315/565/1/012038

[26] Mojiri, Amin, John L. Zhou, Harsha Ratnaweera, Akiyoshi Ohashi, Noriatsu Ozaki, Tomonori Kindaichi, and Hiroshi Asakura. "Treatment of landfill leachate with different techniques: an overview." *Water Reuse* 11, no. 1 (2021): 66-96. https://doi.org/10.2166/wrd.2020.079

[27] Hussein, Munirah, Kenichi Yoneda, Zuhaida Mohd-Zaki, Amnorzahira Amir, and NorÁzizi Othman. "Heavy metals in leachate, impacted soils and natural soils of different landfills in Malaysia: An alarming threat." *Chemosphere* 267 (2021): 128874. https://doi.org/10.1016/j.chemosphere.2020.128874

[28] Carvajal-Flórez, Elizabeth, and Santiago-Alonso Cardona-Gallo. "Technologies applicable to the removal of heavy metals from landfill leachate." *Environmental Science and Pollution Research* 26 (2019): 15725-15753. https://doi.org/10.1007/s11356-019-04888-7

[29] Li, Wei, Xiaowen Ding, Min Liu, Yuewen Guo, and Lei Liu. "Optimization of process parameters for mature landfill leachate pretreatment using MAP precipitation." *Frontiers of Environmental Science & Engineering* 6 (2012): 892-900. https://doi.org/10.1007/s11783-012-0440-9

[30] Rowe, R. Kerry, Jamie F. VanGulck, and Sandra C. Millward. "Biologically induced clogging of a granular medium permeated with synthetic leachate." *Journal of Environmental Engineering and Science* 1, no. 2 (2002): 135-156. https://doi.org/10.1139/s02-008

[31] Huang, Haiming, Lingyun Huang, Qingrui Zhang, Yang Jiang, and Li Ding. "Chlorination decomposition of struvite and recycling of its product for the removal of ammonium-nitrogen from landfill leachate." *Chemosphere* 136 (2015): 289-296. https://doi.org/10.1016/j.chemosphere.2014.10.078

[32] Muhmood, Atif, Shubiao Wu, Jiaxin Lu, Zeeshan Ajmal, Hongzhen Luo, and Renjie Dong. "Nutrient recovery from anaerobically digested chicken slurry via struvite: Performance optimization and interactions with heavy metals and pathogens." *Science of The Total Environment* 635 (2018): 1-9. https://doi.org/10.1016/j.scitotenv.2018.04.129

[33] Tang, Chongjian, Zhigong Liu, Cong Peng, Li-Yuan Chai, Kensuke Kuroda, Masazumi Okido, and Yu-Xia Song. "New insights into the interaction between heavy metals and struvite: Struvite as platform for heterogeneous nucleation of heavy metal hydroxide." *Chemical Engineering Journal* 365 (2019): 60-69. https://doi.org/10.1016/j.cej.2019.02.034

[34] Manzoor, Muhammed AP, M. Mujeeburahiman, Surya Ram Duwal, and P. D. Rekha. "Investigation on growth and morphology of in vitro generated struvite crystals." *Biocatalysis and Agricultural Biotechnology* 17 (2019): 566-570. https://doi.org/10.1016/j.bcab.2019.01.023

[35] Kemacheevakul, Patiya, Surawut Chuangchote, Sosuke Otani, Tomonari Matsuda, and Yoshihisa Shimizu. "Effect of magnesium dose on amount of pharmaceuticals in struvite recovered from urine." *Water Science and Technology* 72, no. 7 (2015): 1102-1110. https://doi.org/10.2166/wst.2015.313