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A low-cost method using steel-making slag to quench the residual phosphorus from wastewater effluent

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ABSTRACT

This study demonstrates a novel application of steel-making slag for quenching residual phosphorus in wastewater effluent after chemical precipitation. The results showed that the phosphorus removal efficiency was low without the supernatant pH adjustment. Decreased pH of the supernatant resulted in increased removal efficiency. At the optimal conditions (i.e. pH 8.5 and steel-making slag dosage of 5 g/L), approximately 98% phosphorus removal could be achieved with the output level of less than 0.1 mg/L. The results also demonstrated that enhanced phosphorus removal by pH adjustment resulted from the involvement of adsorption in the removal process. This observation was evidenced via the compliance with Langmuir isotherm of the adsorption of phosphorus to steel-making slag at decreased pH. In addition, the results indicated that the presence of inorganic carbon in the supernatant could facilitate phosphorus removal via co-precipitation effects.

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1. Introduction

Phosphorus recovery is essential to prevent the depletion of this important element that is indispensable in the modern economy. Indeed, phosphorus is vital in many aspects of life. It is a key element of all genetic molecules (e.g. DNA), bones, and teeth. Phosphorus is a key fertiliser ingredient for food production. The world is gradually but steadily approaching the depletion of minable phosphate rock reserves unless phosphorus recovery can be realised at large scale to circulate this essential element within a circular economy (Vu et al., 2023).

The total minable phosphate rock worldwide is estimated to be exhausted within the next 80–120 years at the current consumption rate (Liu and Chen, 2014). Phosphorus shortage can cause negative impacts on food security and high-tech

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industries due to the reliance of agricultural production on phosphorus-derived fertilisers as well as of food processing and semi-conductor manufacture on white phosphorus (Jones et al., 2020; Jung et al., 2020). Therefore, the recovery and reuse of phosphorus from nutrient-rich sources (e.g. wastewater) are vital for the sustainable development.

Sludge centrate, a liquid phase obtained from dewatering digested sludge of anaerobic digesters in WWTPs, is a highly nutrient-rich stream (Barua et al., 2019; Soler-Cabezas et al., 2018). A high concentration of phosphorus in this stream offers an opportunity for the recovery process (Vu et al., 2022). Indeed, a previous study already demonstrated the possibility of using calcium and alkali metals from steel-making slag to recover phosphorus via precipitation under the form of calcium phosphate precipitates (Vu et al., 2022). However, the research efforts were only made to maximise the efficiency of the recovery process. Little attention has been paid to downstream processing. The fact is that the residual nutrients remaining in the recovery process effluent were abundant (Vu et al., 2022). The discharge of this stream into the waterway without proper post treatment can cause negative impacts on the surrounding environment (e.g. eutrophication and algae bloom phenomenon) (Conley et al., 2009; Liu and Cinquepalmi, 2021a). Hence, the post treatment of the recovery process effluent is of necessity.

Several methods could be used to remove phosphorus from wastewater. Examples include biological treatment (Nielsen et al., 2019; Zhang et al., 2022), ion exchange (Koh et al., 2022; Wu et al., 2022), adsorption (Wu et al., 2021; Xia et al., 2021; Yang et al., 2021), chemical precipitation (Vu et al., 2022; Ma et al., 2021; Wang et al., 2022), and membrane separation (Li et al., 2021; Liu et al., 2022). However, given usually low concentration of residual phosphorus (i.e. less than 50 mg/L PO₄-P) in the recovery process effluent, treatment technologies such as wetlands, ion exchange, adsorption, and microalgae cultivation are preferred as the economic aspects of treatment are taken into account (Barca et al., 2014; Bunce et al., 2018). Of these methods, adsorption is the most straightforward and extensively investigated in full-scale operations for phosphorus removal (Jia et al., 2022; Jonidi Jafari and Moslemzadeh, 2022). However, the cost of adsorbent materials and/or desorption process are limitations to hinder the wide applications of this technology (Jonidi Jafari and Moslemzadeh, 2022). To address these challenges, using secondary or by-products (e.g. steel-making slag and red mud) from steel and aluminium industries to remove phosphorus from wastewater can be a solution due to multiple advantages including reduced treatment costs and beneficial use of waste materials (Vu et al., 2021a). Due to the presence of metal oxides, (e.g. CaO, MgO, Fe₂O₃, and SiO₂) in the composition, steel-making slag could be capable of capturing phosphorus (Jonidi Jafari and Moslemzadeh, 2022; Vu et al., 2021a). It has been demonstrated that using steel-making slag to remove phosphorus from an aqueous solution was feasible (Vu et al., 2021a). The weathered steel-making slag after the removal process could be used directly for road base construction.

In a previous study, steel-making slag was used as a source of calcium and alkali metals for the phosphorus recovery process (Vu et al., 2022). In this process, the calcium and alkali metals were separately leached from steel-making slag and then reacted with phosphate ions in sludge centrate to form calcium phosphate precipitates for recovery (Vu et al., 2022). It is hypothesised that steel-making slag after the leaching process with the residual content of metal oxides might still have a capability of capturing phosphorus, suggesting a promising approach of using the leached slag to quench the residual phosphorus from the recovery process effluent. This approach can simultaneously maximise the use of this material and further accelerate the weathering of steel-making slag for beneficial use. The intensively weathered steel-making slag is less chemically reactive when applied to the road construction. As such, this circular economy-oriented approach is expected to be economically effective and sustainable as the use of external adsorbents is not required for polishing the phosphorus recovery process effluent. Moreover, using the intensively weathered slag from the quenching process as an aggregate for asphalt surfacing can help the road construction corporations minimise the costs of the ambient slag weathering process (i.e. time- and footprint-related costs). In addition, sludge centrate is of high alkalinity (i.e. bicarbonates) (Show et al., 2012). It was reported that the presence of inorganic carbon (e.g. bicarbonates) in the solution could cause competing adsorption effects and reduce the phosphorus removal efficiency (Mendez and Hiemstra, 2019; Song et al., 2002). Given the high alkalinity of sludge centrate (i.e. 1000–5000 CaCO₃ mg/L) (Show et al., 2012), the impacts of inorganic carbon in the recovery process effluent on phosphorus removal by steel-making slag also need to be taken into account.

This study aims to demonstrate the utilisation of weathered steel-making slag for removing residual phosphate in the effluent after phosphorus recovery. It is envisaged that the slag can then be used for road base construction and the post-treated effluent is free of phosphorus for environmental discharge. The impact of key operational parameters and phosphorus removal mechanisms are investigated and discussed. The effects of inorganic carbon present in the recovery process effluent on the removal performance are delineated herein.

2. Materials and methods

2.1. Materials

Steel-making slag was from an electric arc furnace at the Rooty Hill steelwork (Rooty Hill NSW 2766 Australia). The composition of this steel-making slag was characterised and presented elsewhere (Vu et al., 2021a). Briefly, this slag contained 32% CaO, 32% Fe₂O₃, 16% SiO₂, and 6% Al₂O₃. The obtained steel-making slag was washed with distilled water for one minute to remove dirt and immediately dried at 105 °C overnight. The dried steel-making slag was then crushed and sieved to obtain a particle size of less than 0.3 mm. The ground steel-making slag was then stored in an airtight container and purged with N₂ to prevent any reactions with the ambient air until being used in this study.

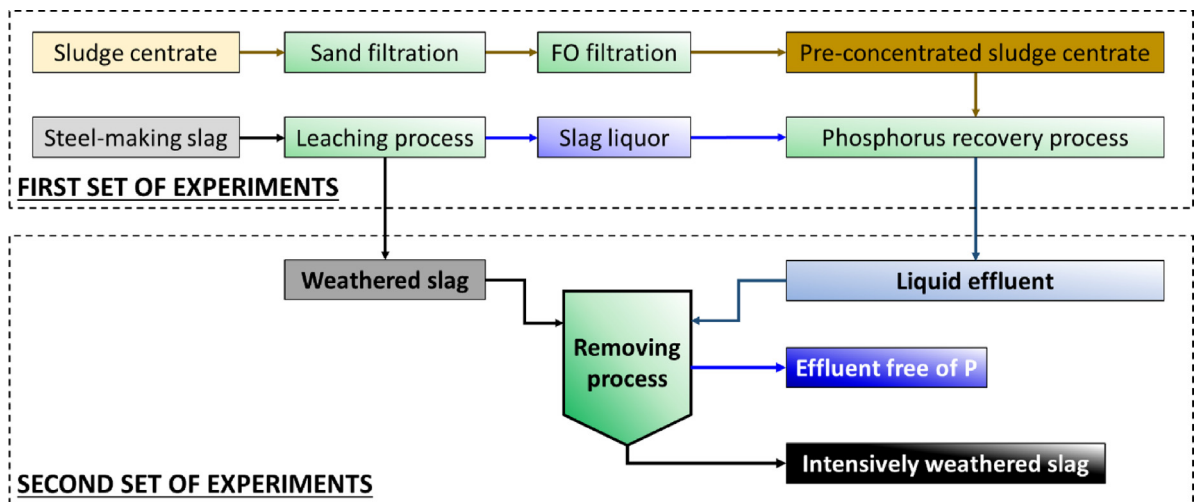


Fig. 1. Description of overall experimental arrangement in this study.

Sludge centrate was collected from a high speed centrifuge at a sewage treatment plant in Sydney (Australia). The sludge centrate was filtered using a 150 μm stainless steel mesh, then pre-treated by sand filtration, and stored at 4 $^{\circ}\text{C}$. The sand filtration column for this pre-treatment has been described in detail elsewhere (Vu et al., 2022). Sludge centrate after sand filtration pre-treatment was used as a feed solution (FS) and pre-concentrated by a forward osmosis (FO) system. This FO system has also been described in detail elsewhere (Vu et al., 2021b). Seawater as a draw solution (DS) for a FO system was taken from a beach in Sydney (Australia) and filtered through 0.45 μm filter paper before use. Flat-sheet thin film composite polyamide FO membranes from Porifera, Inc. (Hayward, California, USA) were used to pre-concentration the phosphorus content in sludge centrate prior to recovery by precipitation. Membrane samples were soaked into deionised (DI) water overnight for complete hydration before use. Key transport properties of this membrane have been reported in a previous study (Vu et al., 2021b).

A lab-scale system to perform the phosphorus recovery process has been also found in a previous study (Vu et al., 2022). Briefly, the recovery system consisted of a glass reactor placed on a magnetic stirrer for mixing, an air rotameter connected to an air blower for ammonia stripping from the solution, and a bottle containing 2M H_2SO_4 acid solution for the capture of the stripped ammonia gas.

2.2. Experimental protocols

In this study, two sets of experiments were conducted in sequence to investigate the feasibility of using steel-making slag to quench the residual phosphorus from the recovery process effluent (Fig. 1). The first set of experiments was to release the process effluent and the weathered slag from the phosphorus recovery process. The detailed experimental procedure in the first batch was similar to that presented in a previous study (Vu et al., 2022). The second set of experiments focused on using the weathered slag to quench the residual phosphorus in the recovery process effluent (Fig. 1).

In the first set of experiments, sludge centrate was pre-treated using the sand filtration system at a filtration rate of 20 m/h. The sand filtered sludge centrate was then pre-concentrated using the FO system until 70% water recovery. The operating conditions of the FO enrichment system were found elsewhere (Vu et al., 2022). The concentrated sludge centrate was used as the first feedstock for the phosphorus recovery process (Fig. 1). A slag liquor as the second feedstock for the phosphorus recovery process was produced via a leaching process by adding steel-making slag of <0.3 mm in particle size into DI water at the dosage of 400 g/L (Fig. 1). Particle size and slag dosage are key factors affecting the quality of the slag liquor and the characteristics of the weathered slag, especially in removing phosphorus. These operating values in this study were selected from the optimised conditions in the previous study (Vu et al., 2022). The slag liquor was obtained by decanting the supernatant of this mixture after being agitated at 200 rpm for 2 h using an orbital shaker. The slag liquor was then stored in an enclosed and N_2 -purged container for further use in the subsequent phosphorus recovery process. The solid phase called weathered slag in the bottom of the glass container after the agitation process was collected and dried at 105 $^{\circ}\text{C}$ for 24 h and stored in an enclosed and N_2 -purged container for further use in a subsequent post-treatment process. Next, the phosphorus recovery process was conducted at the sludge centrate to slag liquor volume ratio of 0.3, reaction time of 120 min, temperature of 20 $^{\circ}\text{C}$, and aeration rate of 1 L/min. At the end of the recovery experiments, the precipitate mixture was kept still for gravity-driven clarification for 1 h. The settling efficiency of the precipitate particles was determined using a 1 L volumetric cylinder. The recovery process effluent was

obtained by decanting the supernatant of the separated precipitate mixture. An aqueous sample of this solution was taken for analysis. The settling efficiency of the formed precipitates was important to evaluate the solid-liquid separation of the mixture solution. This parameter was determined by comparing the volume of the precipitates deposited over time with the initial volume of the mixture (i.e. 1 L) in the volumetric cylinder.

In the second experimental set, a series of batch experiments were performed to evaluate the performance of phosphorus removal from the recovery process effluent using the weathered slag under different experimental conditions (Fig. 1). The impacts of weathered slag dosages, defined as the slag mass to the recovery process effluent volume ratio, on the removal efficiency were investigated. These experiments were conducted with the range of slag dosage from 1 to 10 g/L at room temperature. Experiments to investigate the impacts of the solution pH on the removal efficiency were performed at a pH range from 7.5 to 10.4. The selected pH range for investigation was based on the actual pH of the recovery process effluent (i.e. 10.4), the preliminary screening tests, and the economically feasible adjustment in practice. The optimal pH value is expected to ensure that the excessive consumption of chemicals for pH adjustment is avoided and the phosphorus removal efficiency is not compromised. The pH of the recovery process effluent was adjusted to desired values using 0.1 M HCl acid solution. Unless otherwise stated, the mixture of weathered slag and the recovery process effluent was agitated continuously at 200 rpm on a flat shaker. The duration of these experiments was 72 h. The aqueous phase was then filtered using 1.2 μm glass fibre syringe filters for subsequent analysis. Phosphorus concentration was determined to calculate the amount of phosphorus removed per unit mass of the steel-making slag and removal efficiency as presented in Eqs. (1)–(3).

$$q_t = \frac{V(C_0 - C_t)}{m} \quad (1)$$

$$q_e = \frac{V(C_0 - C_e)}{m} \quad (2)$$

$$\eta = \frac{C_0 - C_t}{C_0} \times 100\% \quad (3)$$

where q_t and q_e are the phosphorus removal capacity of the steel-making slag at time t and equilibrium state, respectively (mg/g); η stands for phosphorus removal efficiency (%); C_0 , C_t and C_e are the phosphorus concentrations at the beginning, at time t and equilibrium state, respectively (mg/L); V is the volume of solution (L) and m is the mass of steel-making slag (g). All experiments were conducted in duplicate.

The compliance with adsorption isotherm models was also examined to understand the removal mechanism. The adsorption isotherm was determined at a constant phosphorus concentration (i.e. the default phosphorus level of the recovery process effluent) and varied dosage of the weathered slag from 1 to 10 g/L. The experiment lasted 72 h to ensure that apparent equilibrium has been achieved. In this study, two isotherm adsorption models including Langmuir and Freundlich were employed to describe the adsorption behaviour of the raw slag and weathered slag. The details of these two models could be found in the Supporting Information.

To evaluate the impacts of inorganic carbon in the recovery process effluent on the removal efficiency, phosphorus removal experiments were also performed using a de-carbonated recovery process effluent. This solution was produced by adjusting its pH to 3.5 using 0.1 M HCl solution followed by aeration at the flow rate of 1 L/min for 30 min. The composition of the recovery process effluent after de-carbonation was characterised to determine the efficiency of the inorganic carbon stripping process.

In addition, the point of zero charge (PZC) of steel-making slag was determined following the salt addition method reported elsewhere (Zu Nurain Ahmad et al., 2018). In detail, three NaCl solutions (500 mL each) at three different concentrations (i.e. 0.01 M, 0.1 M, and 1 M) were prepared by dissolving corresponding amounts of analytical grade NaCl salt into 500 mL of DI water. For each solution, its volume was equally divided into ten conical flasks. It means that each conical flask contained 50 mL NaCl solution. The pH of the NaCl solution in each conical flask was then adjusted to a desired value in the range from pH 2 to pH 13 using 0.1 M NaOH and 0.1 M HCl solutions. Subsequently, 0.5 g of steel-making slag was added to each flask. This mixture was agitated at 150 rpm for 24 h using an orbital shaker. The initial and final pH values of each solution were determined. The difference between the initial and final pH was plotted against the initial pH to identify the pH value at the point of zero charge (pH_{pzc}).

2.3. Analytical methods

Phosphorus (P) and calcium (Ca) concentrations in the sample were analysed using an Inductively Coupled Plasma-Mass Spectroscopy system (ICP-MS, Agilent 7900). The total suspended solid (TSS) content was determined by gravimetric analysis. In detail, 5 mL of the precipitate suspension was filtered through a 1.1 μm pre-weighed glass filter paper. The filter paper was then dried at 105 °C for 8 h to a constant mass. Inorganic carbon (IC) was measured using a total/dissolved organic carbon analyser. pH was measured using a portable HACH HQ40d pH meter. Turbidity was measured using a portable HACH 2100Q IS turbidity meter (HACH, USA).

Table 1

The properties of sludge centrate after different treatment processes (i.e. pre-concentration by FO, recovery, and de-carbonation) (values indicated average \pm standard deviation of three replicate samples).

Parameters	Pre-concentrated sludge centrate	Recovery process effluent	De-carbonated effluent
pH (-)	8.3 \pm 0.1	10.4 \pm 0.1	4.2 \pm 0.1
TSS (mg/L)	17.0 \pm 7.9	-	-
Turbidity (NTU)	13.0 \pm 4.7	0.3 \pm 0.1	0.3 \pm 0.1
Total P (mg/L)	487.2 \pm 5.8	5.6 \pm 0.2	5.6 \pm 0.1
Inorganic carbon (mg/L)	1432.0 \pm 72.0	113.2 \pm 11.3	0
Ca (mg/L)	47.3 \pm 4.4	13.8 \pm 1.8	14.2 \pm 2.0

3. Results and discussions

3.1. Characterisation of the recovery process effluent

Phosphorus content and other relevant parameters in the pre-concentrated sludge centrate before and after chemical precipitation are shown in Table 1. Phosphorus content in the pre-concentrated sludge centrate increased almost threefold after the pre-concentration process (Table 1 and Supporting Information). The composition of slag liquor (i.e. pH of 12.7, turbidity of 0.3 NTU, inorganic carbon content of 53 mg/L, and calcium content of 1078 mg/L) could be favourable for the phosphorus recovery process via precipitation. Indeed, chemical precipitation induced by slag liquor resulted in 99% of phosphorus recovery from the pre-concentrated sludge centrate (Table 1). Nevertheless, a residual phosphorus content of 5.5 mg/L (Table 1) was still observed in the effluent (spent sludge centrate also denoted as the recovery process effluent). This concentration of phosphorus is significantly higher than the permissible value in the effluent discharge to sensitive waterbodies by most water authorities around the world. Thus, results in Table 1 highlighted the need for post-treatment prior to effluent discharge.

The de-carbonation process through the acidification of the effluent could remove inorganic carbon completely but had no impact on phosphorus and calcium contents (Table 1). In other words, apart from the inorganic carbon parameter, the de-carbonated effluent was comparable to the effluent without de-carbonation. Therefore, the comparison in removal efficiency between using the effluent without de-carbonation and de-carbonated effluent could be able to provide an elucidation in the impacts of inorganic carbon on the phosphorus removal process by the slag.

Gravity-driven clarification was capable of separating the formed precipitates effectively from the solution (Fig. 2). The separation step is critical for further treatment of the recovery process effluent. The precipitate settling efficiency increased significantly to 70% during the first 20 min of settling time before gradually reaching 80% after 60 min (Fig. 2). The recovery process effluent was almost transparent as the turbidity decreased to 0.28 NTU, equivalent to 99.7% removal efficiency, compared to fresh sludge centrate (Table 1). The results suggested that the recovery process effluent could be removed from the mixture solution easily only by the decanting method after the gravity-driven settling.

3.2. Impacts of initial pH of the recovery process effluent on the removal efficiency

Overall, weathered slag and raw slag showed similar (or almost identical) performance in phosphorus removal (Fig. 3). Regardless of the solution pH, weathered slag always showed similar phosphorus removal efficiency to raw slag. This observation suggests that after the weathering process, the phosphorus removal capability of slag remained unchanged. This is probably due to the high content of Ca remaining in weathered slag after the leaching process. Indeed, only 0.7% of total Ca in raw slag was released into the slag liquor (data not shown). Moreover, the concentrations of other metals (e.g. Fe, Si, and Al) in the slag liquor were insignificant (i.e. $<2 \mu\text{g/L}$). These results indicate that the weathering process only releases CaO and has negligible impact on the physiochemical properties of the slag.

Decreased initial pH of the recovery process effluent increased the phosphorus removal efficiency significantly (Fig. 3). In addition, it appeared that pH also affected the impacts of slag dosage on the phosphorus removal efficiency. At high pH 10.4, the maximum phosphorus removal efficiency was approximately 50%. Moreover, at this pH value, an increase in the slag dosage of above 5 g/L did not enhance the removal efficiency. At lower pH, the impacts of slag dosage on the removal efficiency were more significant as increased efficiencies were observed at elevated slag dosage. The results demonstrated that phosphorus could be almost completely removed from the solution using weathered slag when pH was adjusted to be lower than 8.5 (Fig. 3). This phenomenon could be explained via pH_{pzc} of weathered slag (i.e. approximately 11.2) (Fig. 4). At lower pH, weathered slag was more negatively charged, encouraging the attractive electrostatic force between the slag surface and phosphate ions in the solution. This force could promote the phosphorus removal mechanism via physical adsorption. The similarity in pH_{pzc} of raw slag and weathered slag (i.e. 11.5 and 11.2, respectively) could explain their comparable phosphorus removal behaviours (Vu et al., 2021a). This result could be supported by the isotherm results discussed further in Section 3.4. The results in Fig. 2 demonstrated that a further decrease in pH to less than 8.5 was unnecessary as no improvements in phosphorus removal were observed.

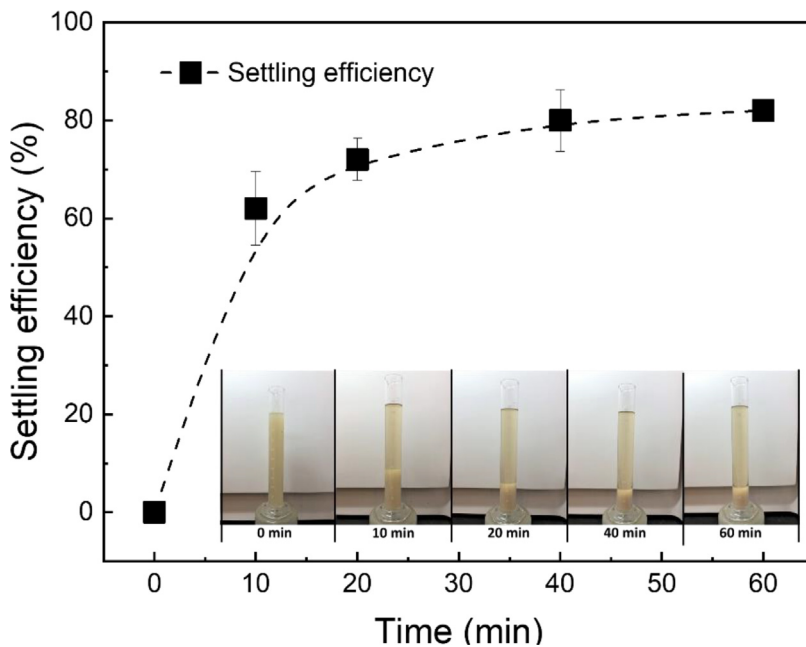


Fig. 2. Settling performance of formed precipitates after the recovery process. Values and error bars are the mean and standard deviation of two replicate experiments.

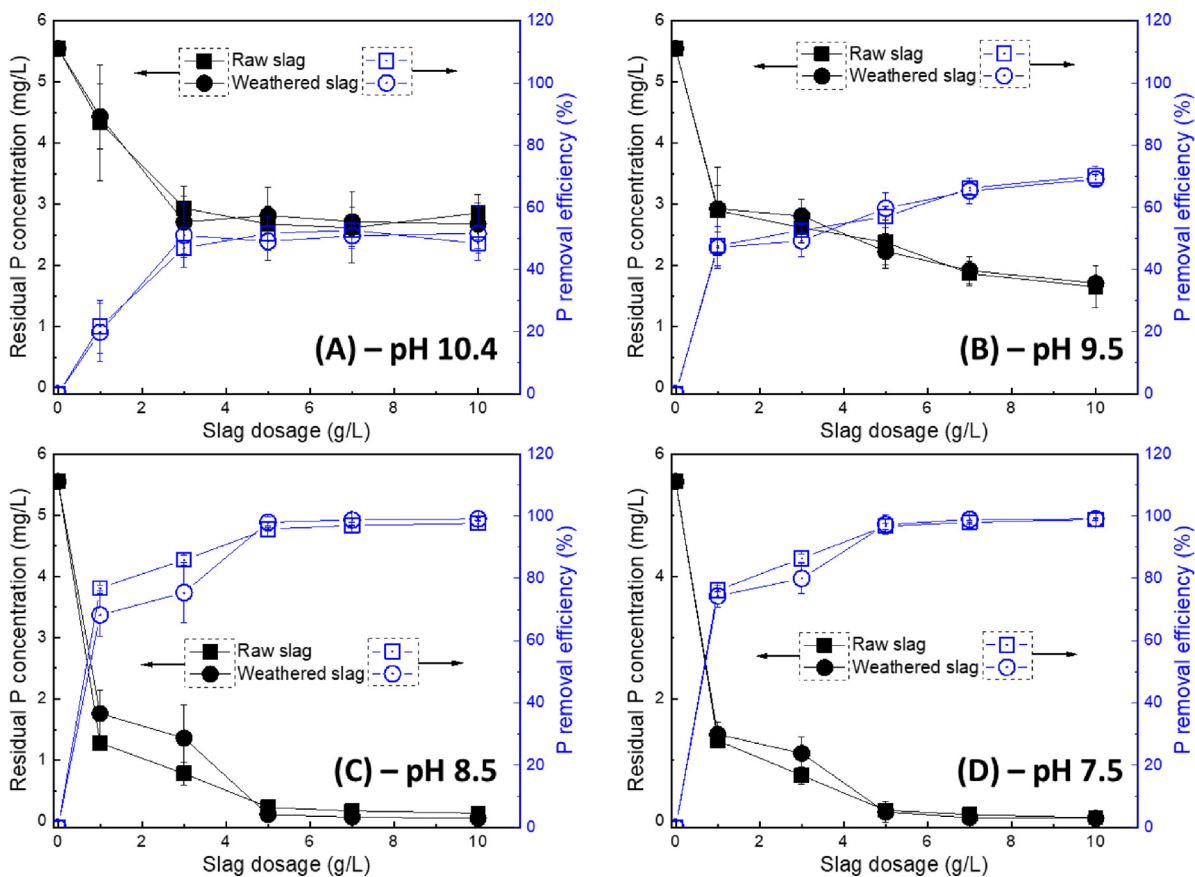


Fig. 3. Impacts of steel-making slag dosage and solution pH: (A) – pH 10.4, (B) – pH 9.5, (C) – pH 8.5, and (D) – pH 7.5 on phosphorus removal efficiency. The experimental conditions: contact time = 72 h, mixing speed = 200 rpm. Values and error bars are the mean and standard deviation of two replicate experiments.

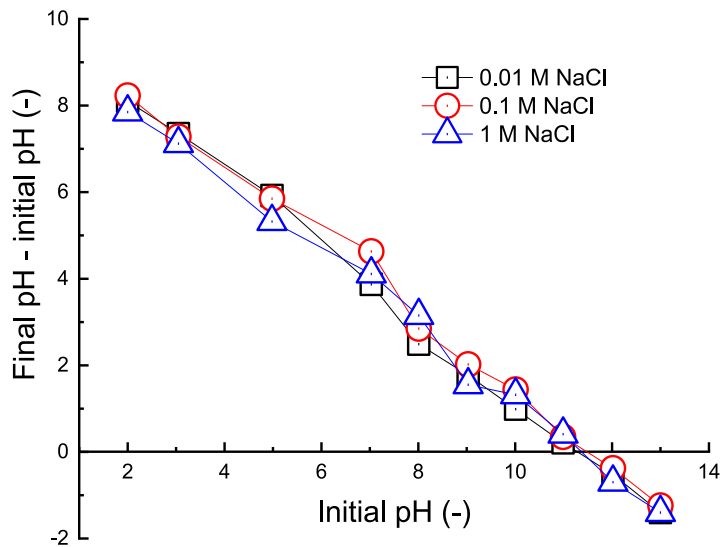


Fig. 4. Average point of zero charge of the weathered slag determined by using NaCl solution at different concentrations.

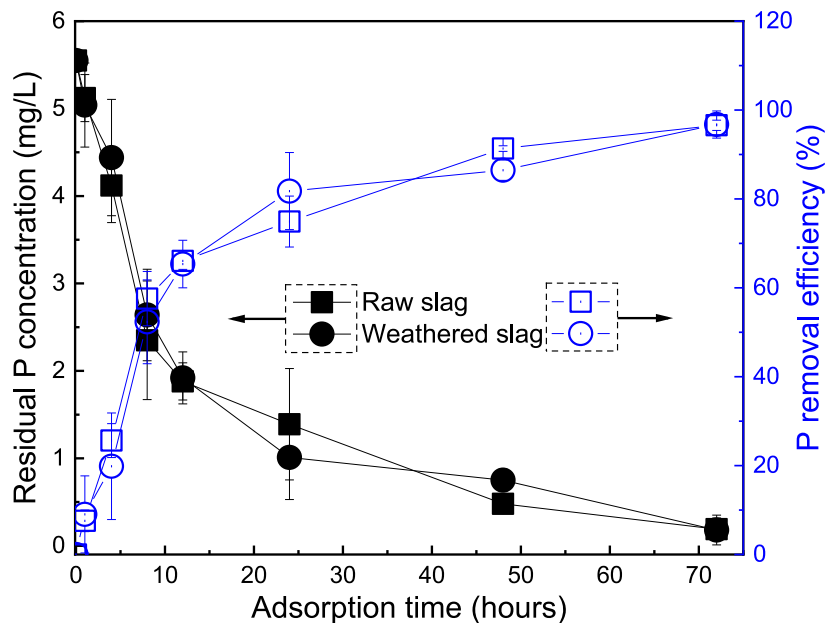


Fig. 5. Kinetics of phosphate adsorption to weathered slag. The experimental conditions: slag dosage = 5 g/L, solution pH = 8.5, mixing speed = 200 rpm. Values and error bars are the mean and standard deviation of two replicate experiments.

3.3. Impacts of adsorption time on the removal efficiency

Prolonged mixing time was necessary for better removal efficiency (Fig. 5). The removal efficiency increased significantly during the first 25 min then decelerated. Given the discussions from the previous study, this result could be explained by the involvement of different removal mechanisms at different reaction time periods (Vu et al., 2021a). In detail, at the early stage of the reaction, the dominant removal mechanism was adsorption via the attractive electrostatic force between phosphate ions and the slag surface as this mechanism was facilitated at a favourable solution pH (i.e. 8.5). Hence, the reaction rate was fast at the beginning. The increasing liberation of Ca into the solution and the elevation of solution pH over time could result in the prevalence of the removal mechanism via Ca–P precipitation under the possible form of hydroxyapatite as discussed thoroughly in the previous study (Vu et al., 2021a). This mechanism explained the slow reaction kinetics.

Table 2
Adsorption isotherms of phosphorus to different types of slag at different solution pH values.

Isotherm model	Parameters	pH 10.4		pH 8.5	
		Raw slag	Weathered slag	Raw slag	Weathered slag
Langmuir	q_{\max} (mg/g)	-0.68	-0.73	5.68	2.45
	K_L (L/mg)	-0.14	-0.14	0.86	6.22
	R^2	0.29	0.34	0.95	0.91
Freundlich	n	0.49	0.59	1.32	2.64
	K_F	0.06	0.09	2.77	2.03
	R^2	0.50	0.42	0.91	0.77

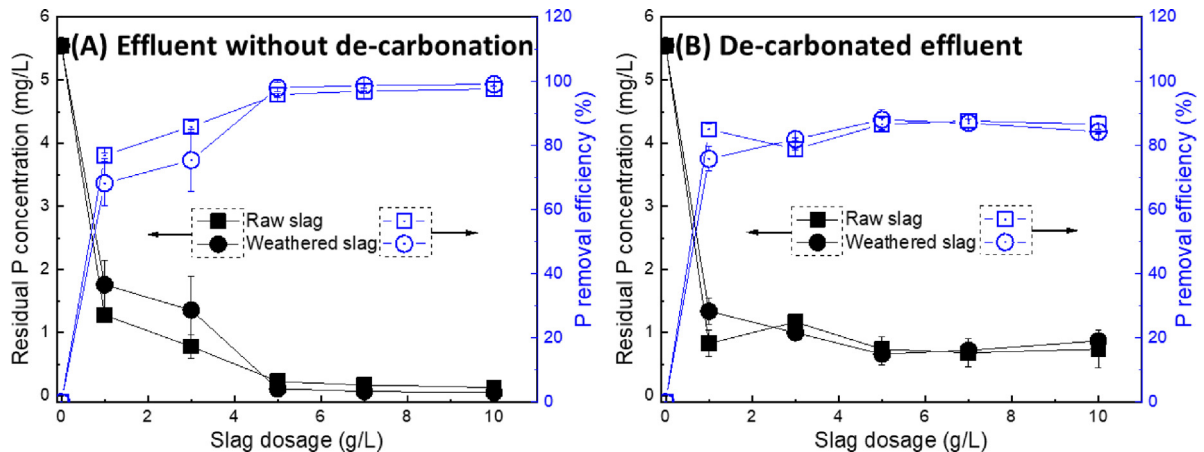


Fig. 6. Impacts of the presence of inorganic carbon on phosphorus removal efficiency by different types of slag using (A) effluent without de-carbonation and (B) de-carbonated effluent. The experimental conditions: initial solution pH = 8.5, contact time = 72 h, mixing speed = 200 rpm. Values and error bars are the mean and standard deviation of two replicate experiments.

3.4. Adsorption isotherm and removal mechanisms

The solution pH could govern the phosphorus removal mechanism by raw and weathered slag (Table 2). The adsorption behaviour of raw slag and weathered slag was described by fitting two basic isotherm models (i.e. Langmuir and Freundlich). The results from Table 2 demonstrated that the adsorption behaviours of raw slag and weathered slag were comparable and dependent on the solution pH. At pH 8.5, the phosphorus adsorption to raw and weathered slag could be described by the Langmuir and Freundlich isotherms (Table 2), confirming adsorption as a major phosphorus removal mechanism. However, both isotherm models could not be used to describe the adsorption behaviour at pH 10.4 as all fitting coefficients (R^2) were very low. The results are consistent with the observations in the previous section. In consideration of R^2 values, the adsorption of phosphorus to both types of slag can be modelled better by the Langmuir isotherm rather than the Freundlich isotherm.

3.5. Impacts of inorganic carbon in the recovery process effluent on the removal efficiency

Results from this study show that bicarbonate content in the solution can affect phosphorus removal (Fig. 6). In fact, de-carbonation of the recovery process effluent decreased the phosphorus removal by the weathered slag. In other words, the presence of inorganic carbon in the recovery process effluent facilitated the phosphorus removal performance (Fig. 6). The results from Fig. 6 demonstrated that regardless of the type of slag used, the phosphorus removal efficiency decreased by approximately 20% when inorganic carbon was removed completely from the recovery process effluent. This observation could be probably due to the non-participation of the co-precipitation of calcium carbonate and calcium phosphate in the absence of inorganic carbon in the de-carbonated recovery process effluent. When the recovery process effluent was used, the co-precipitation of calcium carbonate and calcium phosphate occurred as evidenced by the coincidence of high phosphorus and inorganic carbon removal behaviours and low final calcium content in the solution at the end of the experiment (Fig. 7). Moreover, a significant increase in the final calcium content was observed in the absence of inorganic carbon, confirming no occurrence of calcium carbonate precipitation (Fig. 7). The promoted phosphorus removal efficiency by adsorption by the co-precipitation in the presence of carbonate ions has also been reported in the literature (Liu and Cinquepalmi, 2021b).

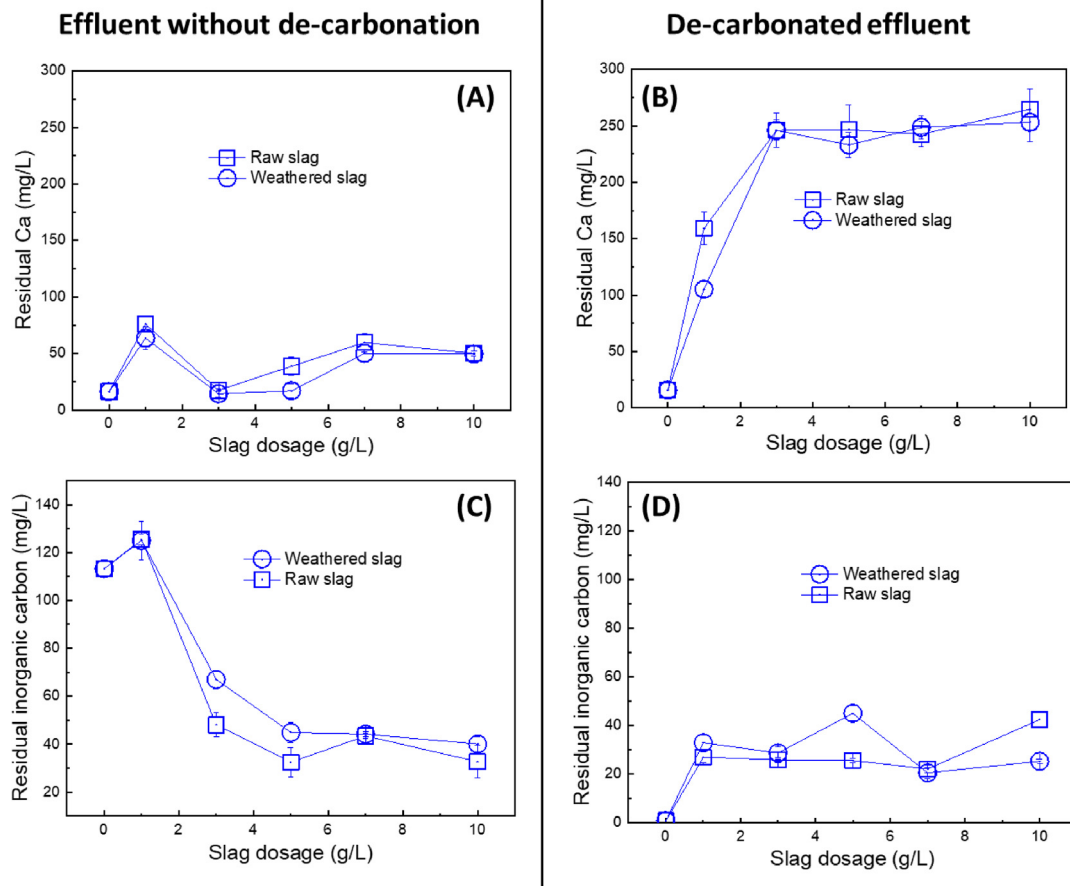


Fig. 7. Changes in (A and B) residual Ca and (C and D) residual inorganic contents in the effluent without de-carbonation and the de-carbonated effluent, respectively during the post treatment under different dosages of slag. The experimental conditions: initial solution pH = 8.5, contact time = 72 h, mixing speed = 200 rpm. Values and error bars are the mean and standard deviation of two replicate experiments.

4. Conclusions

This study has successfully demonstrated the feasibility of using the weathered slag after the slag-involved recovery process to quench the residual phosphorus from itself wastewater effluent. The results demonstrated that the leaching process for phosphorus recovery had negligible impacts on the phosphorus removal capacity of the slag as evidenced by the comparable removal performance between weathered slag and raw slag. The results also showed that the phosphorus removal efficiency was low without the adjustment of the recovery process effluent pH. Decreased pH of the recovery process effluent resulted in increased removal efficiency. At the optimal conditions (i.e. pH 8.5 and steel-making slag dosage of 5 g/L), approximately 98% phosphorus removal could be achieved with the output level of less than 0.1 mg/L. In addition, the results indicated that enhanced phosphorus removal by pH adjustment resulted from the involvement of adsorption in the removing process. This observation was evidenced via the compliance with Langmuir isotherm of the adsorption of phosphorus to slag at decreased pH. Furthermore, this study indicated that the presence of inorganic carbon in the recovery process effluent could facilitate phosphorus removal via co-precipitation effects. It is envisaged that after the removal process, the intensively weathered and less chemically reactive slag could be used for road construction. However, due to the phosphorus-containing properties of slag after the removal process, further studies are needed to investigate the phosphorus-slag bonding stability in order to minimise any potential negative impacts on the environment upon its applications.

CRedit authorship contribution statement

Minh T. Vu: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Hung C. Duong:** Data curation, Visualization, Writing – review & editing. **Qilin Wang:** Validation, Visualization, Writing – review & editing. **Zhengqing Cai:** Validation, Visualization, Writing – review & editing. **Ngoc**

Bich Hoang: Validation, Visualization, Writing – review & editing. **Nga Tran Thi Viet:** Validation, Visualization, Writing – review & editing. **Long D. Nghiem:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.eti.2023.103181>.

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