

Research Article

Effect of lime application on phosphorus adsorption and desorption in post-active acid sulfate soil, Thailand

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Abstract

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The application of lime is the general method of improving acid sulfate soils. However, if a lot of lime is applied, it can reduce the bioavailability of nutrients in the soil, especially phosphorus. The objective of this study was to investigate the effects of liming at different rates on the availability, adsorption, and desorption of phosphorus in two post-active acid sulfate soils (Ay and Se). The experiment was performed in the laboratory. The experiment was laid out in a completely randomized design (CRD) with four treatments and three replicates, i.e., the application of lime at a rate of 0 (control), 0.5, 1.0, and 2.0 times the lime requirement (LR). The lime requirements of the soils in the Ay and Se were 5,690 and 12,250 kg CaCO₃/ha, respectively. The finding revealed that increasing the amount of lime could increase soil pH, available phosphorus, and the phosphorus activation coefficient. Application of lime at a dosage of 1.0-2.0 LR resulted in the highest phosphorus adsorption maximum (Q_m) (380 mg/kg), while 0.5 LR resulted in the lowest Q_m (353 mg/kg) in Se soil only. As lime dosage increased, phosphorus desorption maximum (D_m) and phosphorus desorption ratio (D_r) increased, with 2.0 LR yielding the highest values (124 mg/kg and 23.6 percent for Ay soil, and 77.3 mg/kg and 20.3 percent for Se soil, respectively). The results suggested that applying lime according to the lime requirement test, especially 2.0 LR, is the best option to promote the release of phosphorus in post-active acid sulfate soils.

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Introduction

In Thailand, acid sulfate soil is the main problem for rice cultivation in the central region, especially in the provinces of Nakhon Nayok, Pathum Thani, Prachin Buri, and Phra Nakhon Si Ayutthaya (Attanandana and Vacharotayan, 1986). Acid sulfate soils can be classified as active acid sulfate soils and post-active acid sulfate soils. Both types of soils differ in that the pH of the active acid sulfate soil is less than 4, while

the pH of the post-active acid sulfate soil is higher than 4 (Fanning, 2012). Agricultural management through liming, drainage, irrigation, and cultivation of rice plants with periodic flooding can convert active acid sulfate soils to post-active acid sulfate soils because the above measures increase soil pH (Sukitprapanon et al., 2016). The main problem of acid sulfate soils was inhibition of nutrient mineralization, fixation of certain elements (especially phosphorus), toxic levels of sulfide, iron, and aluminum, and inhibition of

decomposition of organic residues by microorganisms in the soil (Attanandana and Vacharotayan, 1986; Sukyankij et al., 2023). Phra Nakhon Si Ayutthaya is a province in the central region of Thailand. Most of the soils in the area are post-active acid sulfate soils (Ayutthaya and Sena soil series), which cover about 75-80% of the area of the province (Division of Soil Survey and Soil Resource Research, 2019). Although post-active acid sulfate soils have a soil pH greater than 4, at this pH, some toxic metals (Fe, Al, or Mn) are released into the soil solution (Sukitprapanon et al., 2018), reducing the availability of plant nutrients, especially phosphorus (Sukyankij et al., 2023).

Phosphorus is an important nutrient for plant development. Under acidic soil conditions, iron and aluminum are increasingly released into the soil solution, where they are precipitated with phosphorus and converted to insoluble forms (Fe-P, Al-P) (Penn and Camberato, 2019). The nature of adsorption and desorption of phosphorus from solid soil phases and its release into ions (liquid phases) are important aspects of the behavior of phosphorus in soil (Ghodszad et al., 2022), especially in acid sulfate soils. The adsorption process in the soil is able to limit the availability of phosphorus, while the desorption process leads to the loss of available phosphorus from the soil. In the same way, phosphorus is taken up by plants from the desorption process. However, the phosphorus from the desorption process also causes eutrophication in the water source (Eslamian et al., 2021). The effectiveness of phosphorus adsorption depends on phosphorus desorption and is directly related to the transition of phosphorus in the soil from the solid to the liquid phase. Therefore, the adsorption and desorption process of phosphorus in soil is important when it comes to phosphorus being utilized by plants (Yang et al., 2019).

Lime material, such as ground limestone, has a high calcium carbonate content and is often used as a soil conditioner to meliorate acid sulfate soils by raising the pH of the soil, reducing exchangeable aluminum, and decreasing the adsorption of phosphorus. Sorption of phosphorus by certain elements in lime material compounds, including Ca^{2+} and Mg^{2+} , may reduce the availability of phosphorus in soils. On the other hand, adsorption of the above cations (Ca^{2+} and Mg^{2+}) to the negative surface charge of lime can reduce phosphorus adsorption or precipitation reactions in soils (Eslamian et al., 2021). Normally, the amount of lime applied to improve acidic soils is determined by a lime requirement test (Mosharrof et al., 2021), where the goal is to raise the soil pH to 6.5.

Thus, the objectives of this research were (1) to study the adsorption and desorption of phosphorus in post-active acid sulfate soils with different lime contents in batch experiments and (2) to explain the availability of phosphorus at different lime addition rates.

Materials and Methods

Study area and experimental setup

The area of this study was Phra Nakhon Si Ayutthaya province, Thailand. The soils used for the experiment were taken only from soil series identified as post-active acid sulfate soils, i.e., the Ayutthaya (Ay) and Sena (Se) soil series. The Ay soil (Vertic Endoaquepts) was collected in Krachang sub-district, Bang Sai district (14°29'42.94"N 100°49'94.25"E) and the Se soil (Sulfic Endoaquepts) was collected in Chai Na sub-district, Sena district (14°27'74.09"N 100°35'76.80"E) (Division of Soil Survey and Soil Resource Research, 2019). Soil samples from each site were collected at 0-20 cm depth in the paddy fields after harvesting the rice plant. Samples were air-dried, ground, and sieved through a 2-mm sieve before analyzing. Soil properties before the start of the experiment consisted of soil texture (Gee and Bauder, 1986), soil pH (Thomas, 1996), saturated electrical conductivity (Rhoades, 1996), organic matter (Walkley and Black, 1934), available phosphorus (Bray and Krutz, 1945), and exchangeable potassium, calcium, and magnesium (Thomas, 1982) and were analyzed (Table 1).

The basic characteristics of the soil used for the experiment were clay texture for both soils and strongly acidic for the Ay soil (pH = 5.12), while the Se soil was very strongly acidic (pH = 4.58). Both soils had no saline and very high organic matter content (49.1 and 50.2 g/kg for Ay and Se soils, respectively). The available phosphorus was low and medium in the Se (9.8 mg/kg) and Ay soils (20.1 mg/kg), respectively. The potassium, calcium, and magnesium content of Ay soil was very high (125 mg/kg), high (2,368 mg/kg), and high (403 mg/kg), respectively, while Se soil had a high content of the three elements (98, 2,418 and 443 mg/kg for potassium, calcium, and magnesium, respectively). All soil chemical properties were interpreted according to the information provided by the Land Development Department and FAO project staff (1973).

The lime material used for the experiment was calcium carbonate (AR grade) purchased from Central Drug House (P) Ltd. in New Delhi, India. The amount of lime added to the soils was based on the lime requirement test using the Woodruff buffer method (Woodruff, 1948). Four amounts of lime (0, 0.5, 1, and 2 times the lime requirement test) were used for this experiment. Lime requirements values for the Ay and Se soil series were 5,690 and 12,250 kg CaCO_3/ha , respectively. Therefore, 0, 2,845, 5,690, and 11,380 kg CaCO_3/ha were used for the Ay soils, and 0, 6,125, 12,250, and 24,500 kg CaCO_3/ha for the Se soils. In the study herein, a laboratory experiment was conducted to test the adsorption and desorption of phosphorus under the influence of lime application. For the laboratory experiments, lime was added to 500 g of the soil samples. Thus, the Ay soil contained 0, 0.73, 1.45, and 2.90 g $\text{CaCO}_3/500$ g soil, and the Se

soil contained 0, 1.56, 3.13, and 6.26 g CaCO₃/500 g soil, corresponding to 0, 0.5, 1, and 2 times the lime requirement tested for the soil. Each soil sample was placed in a plastic box (15x23x8 cm) and mixed with lime in varying amounts. Deionized water was added to the soil, stirred until the soil was muddy, and then incubated for 30 days at room temperature under flooding conditions. The water level in each soil sample was maintained at 3 cm depth above the soil surface throughout the experimental period. After completion of incubation (30 days), the soil sample was dried, ground, sieved through a 2-mm sieve, and stored in a polyethylene bag. Each treatment was performed in triplicate.

Table 1. Physio-chemical properties of the soils prior to the experiment.

Soil properties	Ay soil series	Se soil series
Soil texture	Clay	Clay
Soil pH reaction	5.12 (SA) [†]	4.58 (VSA) [†]
Electrical conductivity, EC _e (dS/m)	1.99 (VL)	1.24 (VL)
Organic matter (g/kg)	49.1 (VH)	50.2 (VH)
Available phosphorus (mg/kg)	20.1 (M)	9.8 (L)
Exchangeable potassium (mg/kg)	125 (VH)	98 (H)
Exchangeable calcium (mg/kg)	2,368 (H)	2,418 (H)
Exchangeable magnesium (mg/kg)	403 (H)	443 (H)
Lime requirement (kg CaCO ₃ /ha)	5,690	12,250

Remarks: [†]The letters in parentheses are interpreted according to Land Classification Division and FAO Project Staff (1973): VSA= very strongly acidic; SA= strongly acidic; VL= very low; VH= very high; L= low; M= medium; H= high.

Total and available phosphorus

Total phosphorus was determined by the vanadomolybdate yellow color method. 1.0 g of dry soil in each treatment was placed in a 75-mL glass tube, and 5 mL of a mixed acid (HNO₃-HClO₄ in a 10:3 (-v/v) ratio) was added (Pequerul et al., 1993). The samples were digested in block digestion at 120 °C for 2 hours. Samples were then removed, cooled, and filtered through No. 5 filter paper. The purified solution was analyzed for total phosphorus using a spectrophotometer at a wavelength of 420 nm (Kuo, 1996). Available phosphorus was measured by the ascorbic acid method. 2.0 g of dry soil was placed in a 100 mL conical flask, and 20 mL of Bray II extractant (0.03 M NH₄F + 0.1 M HCl) was added, shaken for 1 minute, and filtered through No. 5 filter paper. The

purified solution was analyzed for available phosphorus using a spectrophotometer at a wavelength of 880 nm (Kuo, 1996). The phosphorus activation coefficient (PAC) was calculated using the ratio of available to total phosphorus in the soil (Yang et al., 2019).

Phosphorus adsorption and desorption

The batch equilibrium method has been used to study the adsorption and desorption of phosphorus (Yang et al., 2019; Bekele et al., 2020). 0.5 g of dry soil was placed in a 15-mL polypropylene centrifuge tube, and then a 0.01 M CaCl₂ solution containing phosphorus (as KH₂PO₄) was added at concentrations of 0, 2.5, 5, 10, 20, 30, 40, 50, and 60 mg/L at a ratio of 1:20 (soil/solution, w/v). Two drops of chloroform were then added to each tube to inhibit microbial growth. Samples were shaken in an end-over-end shaker at room temperature for 24 hours. After equilibrium was reached, the samples were centrifuged at 3,000 rpm for 10 minutes, filtered, and the amount of phosphorus in the solution was measured using the ascorbic acid method with a spectrophotometer at a wavelength of 880 nm (Kuo, 1996).

The difference between the initial phosphorus concentration (before shaking) and the phosphorus concentration at equilibrium (after shaking) was defined as phosphorus adsorbed by the soils. The soils after adsorption were also used for the desorption experiment. To the remaining soil, 10 mL of a saturated NaCl solution with a pH of 7.0 was added to extract the adsorbed phosphorus; the sample was then shaken, centrifuged, and the supernatant solution was removed. Then, 10 mL of a 0.01 M CaCl₂ solution was added, shaken, and centrifuged using the same method as for adsorption. The phosphorus concentration in the solution was considered as desorbed phosphorus.

Statistical analyses

Langmuir and Freundlich equations were established for the phosphorus adsorption (equations 1 and 3) and desorption (equations 2 and 4) isotherms, with the Langmuir equations described in linear form, while the Freundlich equations were described in logarithmic form.

$$C/Q = C/Q_m + 1/kQ_m \quad (1)$$

$$C/D = C/D_m + 1/kD_m \quad (2)$$

$$Q = aC^{1/n} \quad (3)$$

$$D = aC^{1/n} \quad (4)$$

where: C (mg/L) is the equilibrium phosphorus concentration in the aqueous solution, Q or D (mg/kg) is the amount of phosphorus adsorbed or desorbed per amount of soil at equilibrium, k is a constant related to adsorption or desorption energy, and Q_m or D_m (mg/kg) is the maximum adsorption or desorption capacity, a and 1/n are Freundlich constants relating to sorption capacity and intensity, respectively.

The maximum buffering capacity of soil (MBC) was calculated by multiplying between k and Q_m (Yang et al., 2019). Phosphorus retention ($P_{\text{retention}}$) in soil was computed from the difference between phosphorus adsorption and phosphorus desorption (Ghodszad et al., 2022). The desorption ratio (D_r) was calculated by the ratio between maximum desorption capacity and maximum adsorption capacity (Yang et al., 2019). The difference between total phosphorus, available phosphorus, phosphorus activation coefficient, maximum adsorption or desorption, maximum buffering capacity, and desorption ratio were determined using standard analysis of variance (ANOVA). The different means of the treatments were tested using Duncan's new multiple range test (DMRT) at a significant level of $p < 0.05$.

Results and Discussion

Soil pH and phosphorus content in the soil

Soil pH in post-active acid sulfate soils was significantly affected by the different lime contents, which were statistically significant differences ($p < 0.05$), as shown in Figure 1. The pH of the soil increased as the amount of lime added to the soil increased. Application of lime at the rate of 0.5, 1, and 2 times of the required lime in Ay soil increased the soil pH by 9.0, 17.2, and 28.8 percent, respectively, whereas that of Se soil increased by 17.2, 38.2, and 54.5 percent, respectively, when compared to the control group.

Application of lime in different amounts resulted in significant differences ($p < 0.05$) for available phosphorus and PAC (Table 2). The highest lime application (2.0 LR) provided the highest value of available phosphorus (27.7 mg/kg for Ay soil) and PAC (1.51 and 0.95 percent for Ay and Se soil, respectively). In Se soil, lime application (1.0 LR) gave the highest value of available phosphorus (13.9 mg/kg), which was not significantly different from lime application with 2.0 LR. The control treatment had the lowest values for available phosphorus and PAC in both the Ay and Se soils. There was also no significant difference in total phosphorus between treatments ($p > 0.05$), with values ranging from 1,826 to 1,853 and 1,513 to 1,553 mg/kg for Ay and Se soils, respectively. The application of lime in higher dosage obviously increases the amount of available phosphorus as well as PAC, which is due to the fact that lime contains a lot of calcium and carbonate that produces Ca^{2+} and HCO_3^- . Both Ca^{2+} and HCO_3^- are able to remove adsorbed H (H^+) in acidic soil. As a result, the pH of the soil increases (Sukyankij et al., 2023). Normally, the release of phosphorus in the soil into the available form (H_2PO_4^- or HPO_4^{2-}) depends on the pH reactions in the soil. Johan et al. (2021) mentioned that the bioavailability of phosphorus is greatest at pH 6.5 for mineral soils and at pH 5.5 for organic soils. Thus, the pH of the soil is near 6.5, and

there is higher available phosphorus than soil with a low pH or higher of 6.5. At PAC, the ratio of available phosphorus to total phosphorus is given. It indicates the degree of difficulty with which the conversion of total phosphorus to available phosphorus occurs. The higher PAC indicates that more phosphorus is available to promote plant growth (Yang et al., 2019).

The results of the experiment showed that an increased amount of lime could promote the conversion of unavailable phosphorus (total phosphorus) into available form (available phosphorus). According to Mkhonza et al. (2018), the effects of lime application on nitrogen and phosphorus availability in humic soils in South Africa were studied, and it was reported that the application of a higher lime rate could decrease Al-P and Fe-P content and increase soluble phosphorus and Ca-P. The study also suggests that applying more lime to acidic-humic soils could increase mineral nitrogen (ammonium and nitrate) and extractable phosphorus and improve plant productivity, but that the high release of mineral nitrogen resulting from lime application could reduce soil organic matter in the long term.

Phosphorus adsorption and desorption equations

The common models used to explain the characteristics of phosphorus adsorption and desorption in soil are the Langmuir and Freundlich equations. The adsorption data for the two equations for two soils (Ay and Se soils) are shown in Table 3. In Ay soil, fitting of adsorption data by the Langmuir equation ($R^2 = 0.9127-0.9650$) showed higher goodness of fit compared to the Freundlich equation ($R^2 = 0.8421-0.8798$). For the Se soil, both the Langmuir and Freundlich equations were excellent, and the R^2 values were high ($R^2 = 0.9723-0.9793$ for the Langmuir and $R^2 = 0.9526-0.9682$ for the Freundlich equation). Desorption data for the two equations of two soils (Ay and Se soils) are given in Table 4.

The Langmuir equation proved to be much better at explaining the characteristics of phosphorus desorption compared to the Freundlich equation. The R^2 values of the Langmuir equation in the Ay and Se soils were $R^2 = 0.8535-0.9287$ and $R^2 = 0.9440-0.9720$, respectively, while the Freundlich equation had lower R^2 values than the Langmuir equation, namely $R^2 = 0.6483-0.7936$ and $R^2 = 0.7417-0.8093$ for the Ay and Se soils, respectively.

The results of the experiment illustrated that the Langmuir equation describes the adsorption and desorption processes better than the Freundlich equation. This indicated that the adsorption and desorption sites of these soils were monolayers and that one molecule of phosphorus could be adsorbed at each site of soil specific surface area. Once a surfactant molecule occupies a site, no further adsorption and desorption occurs (Kalam et al., 2021). However, the Langmuir adsorption equation has also been used to calculate other parameters related to the adsorption

and desorption of phosphorus, such as the maximum adsorption and desorption capacity (Q_m and D_m), the

phosphorus adsorption or desorption energy constant (k), and the MBC parameter. (Yang et al., 2019).

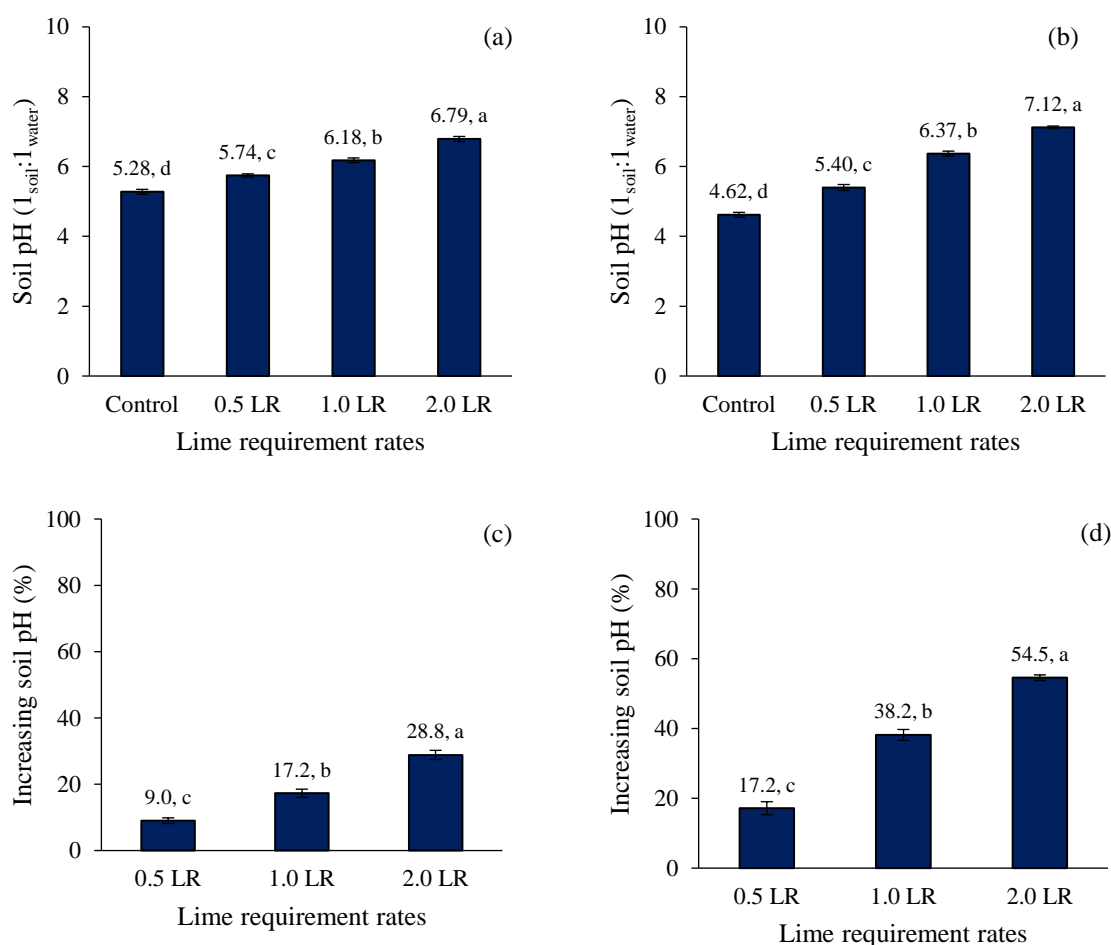


Figure 1. Effect of different lime contents on soil pH reaction in two soil; (a) and (c) are soil pH and percentage of increasing soil pH in the Ay soil, and (b) and (d) are in the Se soil; Increasing soil pH (%) was calculated by comparison with the control treatment; LR is the lime requirement test; The letters above the histograms indicate a statistical significance at $p < 0.05$ level using the DMRT test; Vertical bars represented standard deviation ($n=3$).

Table 2. Effects of different lime contents on total phosphorus, available phosphorus, and PAC in two soils.

Treatments	Total phosphorus (mg/kg) †		Available phosphorus (mg/kg) †		PAC (%) †	
	Ay soil	Se soil	Ay soil	Se soil	Ay soil	Se soil
Control	1,831	1,553	20.9 ^c	10.6 ^c	1.12 ^c	0.68 ^c
0.5 LR	1,826	1,513	22.8 ^b	13.0 ^b	1.24 ^b	0.86 ^b
1.0 LR	1,829	1,529	23.4 ^b	13.9 ^a	1.28 ^b	0.94 ^a
2.0 LR	1,835	1,518	27.7 ^a	13.7 ^{ab}	1.51 ^a	0.95 ^a
F-test	ns	ns	*	*	*	*
CV (%)	1.5	1.2	4.6	3.0	4.8	3.2

Remarks: † Mean values with different lowercase letters in the same column indicate a significant difference according to DMRT at $p < 0.05$; * is a significant difference at the 0.05 probability level, and ns is no significant difference; LR is the lime requirement test; PAC is the phosphorus activation coefficient.

Table 3. Effects of different lime contents on phosphorus adsorption equation in two soils.

Treatments	Langmuir equation		Freundlich equation	
	$C/Q = C/Q_m + 1/kQ_m$	R^2	$Q = aC^{1/n}$	R^2
Ay soil				
Control	$C/Q = 0.0020C + 0.0043$	0.9127	$Q = 135C^{0.5857}$	0.8421
0.5 LR	$C/Q = 0.0021C + 0.0041$	0.9527	$Q = 133C^{0.5887}$	0.8653
1.0 LR	$C/Q = 0.0021C + 0.0037$	0.9650	$Q = 139C^{0.5834}$	0.8798
2.0 LR	$C/Q = 0.0019C + 0.0042$	0.9283	$Q = 140C^{0.6370}$	0.8764
Se soil				
Control	$C/Q = 0.0027C + 0.0030$	0.9723	$Q = 139C^{0.3964}$	0.9526
0.5 LR	$C/Q = 0.0028C + 0.0031$	0.9777	$Q = 135C^{0.3743}$	0.9682
1.0 LR	$C/Q = 0.0026C + 0.0023$	0.9793	$Q = 154C^{0.3821}$	0.9554
2.0 LR	$C/Q = 0.0026C + 0.0024$	0.9780	$Q = 152C^{0.4006}$	0.9558

Remarks: C is the phosphorus concentration in solution at equilibrium (mg/L); Q is the adsorbed phosphorus concentration (mg/kg); Q_m is the maximum adsorbed phosphorus concentration (mg/kg); k is a constant relating to binding strength; a and 1/n are Freundlich constants relating to sorption capacity and intensity, respectively.

Table 4. Effects of different lime contents on phosphorus desorption equation in two soils.

Treatments	Langmuir equation		Freundlich equation	
	$C/D = C/D_m + 1/kD_m$	R^2	$D = aC^{1/n}$	R^2
Ay soil				
Control	$C/D = 0.0116C + 0.0043$	0.8535	$D = 79.4C^{0.6947}$	0.7936
0.5 LR	$C/D = 0.0107C + 0.0037$	0.9287	$D = 71.7C^{0.5081}$	0.7075
1.0 LR	$C/D = 0.0099C + 0.0033$	0.9096	$D = 78.8C^{0.5044}$	0.6957
2.0 LR	$C/D = 0.0081C + 0.0030$	0.9171	$D = 90.5C^{0.4869}$	0.6483
Se soil				
Control	$C/D = 0.0210C + 0.0024$	0.9440	$D = 44.9C^{0.3727}$	0.8077
0.5 LR	$C/D = 0.0220C + 0.0018$	0.9720	$D = 42.9C^{0.3149}$	0.8093
1.0 LR	$C/D = 0.0166C + 0.0009$	0.9620	$D = 56.1C^{0.3567}$	0.7259
2.0 LR	$C/D = 0.0129C + 0.0002$	0.9367	$D = 79.6C^{0.3795}$	0.7417

Remarks: C is the phosphorus concentration in solution at equilibrium (mg/L); D is the desorbed phosphorus concentration (mg/kg); D_m is the maximum desorbed phosphorus concentration (mg/kg); k is a constant relating to binding strength; a and 1/n are Freundlich constants relating to sorption capacity and intensity, respectively.

Phosphorus adsorption and desorption parameters

The amount of phosphorus adsorption sites per unit weight of soil indicates the maximum adsorption capacity for phosphorus (Q_m) and is often applied to evaluate the phosphorus adsorption capacity of soil, while the maximum phosphorus desorption capacity (D_m) is used as the amount of phosphorus released when the adsorbent is saturated with phosphorus (Yang et al., 2019). Application of lime at higher dosage resulted in higher Q_m , especially in Se soil, and treatment of 1.0 and 2.0 LR resulted in the highest Q_m (380 mg/kg), while 0.5 LR gave the lowest Q_m (353 mg/kg) (Table 5). This indicates that the application of lime in an amount equivalent to 1.0-2.0 times the lime requirement in Se soil led to an increase in phosphorus fixation, while the Q_m value in Ay soil, with values ranging from 469-527 mg/kg, showed no significant difference ($p > 0.05$). Normally, the application of lime in acidic soils should lower Q_m value because the lime raises the pH of the soil and neutralizes the cation (Al^{3+} and Fe^{3+}) that bound the phosphate ions in the soil solution (Bekele et al., 2020). However, the Q_m value tended to increase as the amount of lime increased, especially in the Se soil, because the amount of lime

applied was higher in the Se soil (6,125-24,500 kg $CaCO_3/ha$) than in the Ay soil (2,845-11,380 kg $CaCO_3/ha$), which increased the adsorption sites in the soil. Similarly, the phosphorus bonding energy (k) and MBC values, both values were significantly increased with the increasing amount of lime ($p < 0.05$), but only in Se soil. A higher k value indicates greater phosphorus adsorption, while a higher MBC value means that more phosphorus is adsorbed (Yang et al., 2019).

The results indicated that the higher the amount of lime, the more phosphorus was adsorbed, especially in the Se soil. In contrast to the report by Holford et al. (1994), they also found that higher lime content lowered both k and MBC values. The results indicated that in post-active acid sulfate soils, the application of more lime (1.0-2.0 times the lime requirement) resulted in increased phosphorus adsorption, especially in low pH soils (Se soils). The application of lime in different amounts had a significant effect on the maximum phosphorus desorption capacity (D_m) ($p < 0.05$). As the amount of lime increased, the D_m value increased, and treatment with 2.0 LR resulted in the highest D_m values for both soils (124 mg/kg for Ay

and 77.3 mg/kg for Se). This result was similarly found for the phosphorus desorption ratio (D_r). The different lime applications differed statistically in D_r ($p < 0.05$). Application of 2.0 LR resulted in the highest D_r value for both soils (23.6 and 20.3 percent for Ay and Se, respectively), while the control treatment (no lime application) resulted in the lowest D_r value (17.8 and 13.0 percent for Ay and Se, respectively). The application of lime may increase phosphorus adsorption in acidic soils. This result is consistent with that of Bekele et al. (2020), who reported that application of lime at the level of the lime requirement test can increase phosphorus desorption in the soil of Bambasi district in western Ethiopia by about 25-75 percent, compared to no lime application. However, in calcareous soils, increasing the amount of lime

produced a negative result in phosphorus desorption. Eslamian et al. (2021) studied the application of lime to improve phosphorus adsorption capacity and reduce phosphorus desorption in soils in Canada. They found that the application of lime to calcareous soils significantly reduced the cumulative desorption of phosphorus. Regarding the amount of P retention in soil ($P_{\text{retention}}$), the effect of the different amounts of lime was not statistically different ($p > 0.05$); $P_{\text{retention}}$ ranged from 367-404 and 302-319 for Ay and Se soil, respectively. The results indicate that the application of lime, especially 2.0 times the lime requirement is the best choice for soil improvement if they want to promote the transfer of phosphorus in this soil from unavailable (adsorbed phosphorus) to available (desorbed phosphorus).

Table 5. Adsorption and desorption parameters for different treatments in two soils.

Treatments	Q_m (mg/kg) †	k (L/mg) †	MBC (L/kg) †	D_m (mg/kg) †	$P_{\text{retention}}$ (mg/kg) †	D_r (%) †
Ay soil						
Control	492	0.47	235	87 ^c	404	17.8 ^d
0.5 LR	484	0.51	245	93 ^{bc}	390	19.3 ^c
1.0 LR	469	0.58	274	101 ^b	367	21.6 ^b
2.0 LR	527	0.46	240	124 ^a	403	23.6 ^a
F-test	ns	ns	ns	*	ns	*
CV (%)	4.2	9.8	6.5	1.8	5.7	5.7
Se soil						
Control	366 ^b	0.91 ^b	340 ^b	47.5 ^c	318	13.0 ^c
0.5 LR	353 ^c	0.91 ^b	320 ^c	45.4 ^c	307	12.8 ^c
1.0 LR	380 ^a	1.13 ^a	429 ^a	60.3 ^b	319	15.9 ^b
2.0 LR	380 ^a	1.13 ^a	423 ^a	77.3 ^a	302	20.3 ^a
F-test	*	*	*	*	ns	*
CV (%)	2.1	3.6	5.2	3.0	2.9	4.4

Remarks: † Mean values with different lowercase letters in the same column indicate a significant difference according to DMRT at $p < 0.05$; * is a significant difference at the 0.05 probability level, and ns is no significant difference; Q_m is the maximum phosphorus adsorption capacity; k is the constant related to the adsorption energy of phosphorus; MBC is the maximum buffering capacity of soil; D_m is the maximum phosphorus desorption capacity; $P_{\text{retention}}$ is the amount of P retention in soil; D_r is the ratio of phosphorus desorption in soil.

Conclusion

In this study, on post-active sulfate soils in Phra Nakhon Si Ayutthaya Province, Thailand, the potentially fixed phosphorus (Q_m) was higher than the released phosphorus (D_m). By applying lime, the available phosphorus could be increased. At the same time, the total phosphorus was converted into a higher available phosphorus. Estimation of adsorption and desorption characteristics in the soil using the Langmuir and Freundlich equations showed that the adsorption and desorption characteristics in both soils were monolayer. This means that a phosphorus molecule could be adsorbed at a point on the specific soil surface, and the molecule was not overlaid. The application of lime in increasing dosages apparently resulted in increased phosphorus adsorption (Q_m), especially in the Se soil. In addition, increasing the amount of lime also increased phosphorus desorption

and the ratio of phosphorus desorption in the Ay and Se soils. The supported parameters (k and MBC) confirmed that the application of more lime could lead to increased phosphorus adsorption in the soil, especially in the Se soil.

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