

Article

Effects of Phosphorus Fertilizer Application Rates on Colloidal Phosphorus Leaching in Purple Soil in Southwest China

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Abstract: Phosphorus (P) lost via leaching from agricultural land is of major concern for water resource managers worldwide, and colloidal phosphorus (CP) may have a high contribution, since it is an important mobile form of P in soil and subsurface drainage. The objective of this study is to relate P fertilization application rates to CP leaching. To eliminate the influence of climate and facilitate the accurate measurement of P contents in different soil layers, we established soil columns to investigate the impacts of fertilizer application rates and timing on P leaching. Therefore, a soil column leaching experiment was undertaken with different P fertilization application rates (0, 20, 40, 100, 200, and 400 mg kg⁻¹) for purple soil in southwest China. P application rates had significant effects on CP and dissolved phosphorus concentrations in the top soils ($p < 0.05$) (e.g., 0–10 cm in this study), and they further increased P leaching loss by 24–375%. CP was the dominant P form and contributed 31–61% to total phosphorus in the leachate. The concentration of different P forms in leachates decreased significantly over time, and the risk of P leaching loss was greater within two weeks after P application ($p < 0.05$). The advisable range of P application rate is recommended to be 0–450 kg ha⁻¹ for agricultural practice, and it is also recommended to keep P fertilizer in the soil for more than two weeks. Some countermeasures, related to application rates and timing, should be taken to minimize the buildup of P in the field and reduce the risk of P leaching.

Keywords: phosphate fertilizer; colloidal phosphorus; leaching loss; purple soil; soil depth; column study



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1. Introduction

Excessive phosphorus (P) fertilization is one of the main causes of agricultural non-point source pollution [1]. Application of P fertilizer can lead to an accumulation of P in the surface soil of farmland and then lead to the leaching of P and pollution of groundwater [2]. During the above processes, the movement of irrigated water and rainfall are the major pathways of P leaching, which subsequently results in the eutrophication of riparian and lacustrine habitats [3,4]. The potential environmental hazard of P leaching depends on several factors such as fertilizer application rates and the mobility of bioavailable P [1,2]. Accordingly, effective management strategies are needed to minimize the risk of P leaching.

The mobility of bioavailable P largely depends on P form. Colloidal phosphorus (CP), referring to P absorbed on colloids, is a main form of P transporting from the soil surface to groundwater. The colloids play an important role in P cycling because of the large P binding capacity and high mobility [5,6]. For example, the contribution rate of CP to soil transportable P was up to 75% [7]. CP accounts for 50% of total phosphorus (TP) concentrations in some rivers and lakes [8]. CP can be easily leached from soil to remain in solution for a long period [9], and it consequently encourages blue–green algal blooms

and accelerates eutrophication rates [10]. Christophe et al. investigated the effect of biogas slurry on CP leaching in paddy topsoil and found that CP in the leachate ranged from 0.002 to 0.03 mg P L⁻¹ contributing 3–26% to TP leaching [11]. Gottselig et al. reported that CP occurred in two size fractions (2–20 nm and 21–300 nm), and they constituted up to 100% of the total P discharge in the Wüstabach catchment [5]. As such, CP leaching from soil to surface water is an important non-point source of eutrophication. Moreover, CP migration results in the redistribution of P in the soil profile. The purple soils are thin Entisols with high erosivity and strong dispersibility with high colloid content, and they dominate agricultural soil types in the upper reaches of the Yangtze River, China [12,13]. Studies have shown that soil colloid can promote the vertical migration of P through soil macropores, and P fertilizer application can affect the downward migration of P in the soil profile [8,9,11]. In addition, some studies suggest that some CP could be directly bioavailable [14,15]. However, there are few studies on the effect of P application on the downward migration of colloidal P in purple soil profile.

The objective of this study is to investigate the P concentration in soil profiles and CP leaching with different P fertilizer application rates and timing. We conducted this study by establishing soil columns with layered soils and fertilized with different amounts and at different times. The time series of P leaching and residual in soils will be measured dynamically to show the processes and discuss the potential impact factors. Our results will demonstrate whether P leaching loss could be minimized by controlling the amount and timing of P application to guide fertilization strategies.

2. Materials and Method

2.1. Soil Collection

Our soil samples were collected from the upper reaches of the Yangtze River (104°34'12"–104°35'19" E and 30°05'12"–30°06'44" N) (Figure 1) at an elevation of 395 m. In this region, the mean annual precipitation is 966 mm. The area is dominated by purple soils formed in purple sandy shale (Typic Calcareous Soil), and they are classified as Entisols according to the World Reference Base for Soil Resources, update 2015 [16]. At the end of April 2017, we collected soils of more than 50 kg from four depths (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm) in nine different areas of an agricultural field. The samples were composited by mixing the samples of the corresponding layers on site. Afterwards, the samples were transported to the laboratory, air-dried at room temperature, grounded to pass through a 2 mm sieve, and analyzed for properties (Table 1).

Table 1. The soil bulk density, pH and concentrations of soil organic matter (SOM), total phosphorus (TP), total nitrogen (TN), total potassium (TK), available phosphorus (AP), available nitrogen (AN), and available potassium (AK) (mean ± SD) from different soil layers in the study area.

Soil layers (cm)	0–10	10–20	20–30	30–40
Bulk density (g cm ⁻³)	1.34 ± 0.08	1.31 ± 0.12	1.39 ± 0.03	1.44 ± 0.18
pH	8.2	8.1	8.0	8.2
SOM (mg kg ⁻¹)	8120.69 ± 229.65	7513.91 ± 470.55	7418.37 ± 283.22	7379.60 ± 336.77
TP (mg kg ⁻¹)	1264.74 ± 165.99	998.26 ± 241.83	972.10 ± 182.74	1007.28 ± 164.45
TN (mg kg ⁻¹)	1003.88 ± 98.74	983.87 ± 106.82	990.11 ± 79.38	873.29 ± 88.37
TK (mg kg ⁻¹)	1729.73 ± 398.02	1583.11 ± 289.38	1542.73 ± 138.29	1603.38 ± 100.28
AP (mg kg ⁻¹)	255.28 ± 5.78	171.01 ± 0.75	152.33 ± 10.37	112.73 ± 3.46
AN (mg kg ⁻¹)	116.36 ± 28.09	100.85 ± 10.86	93.29 ± 3.29	88.94 ± 15.86
AK (mg kg ⁻¹)	120.99 ± 30.64	106.81 ± 10.87	92.31 ± 12.28	98.64 ± 6.96

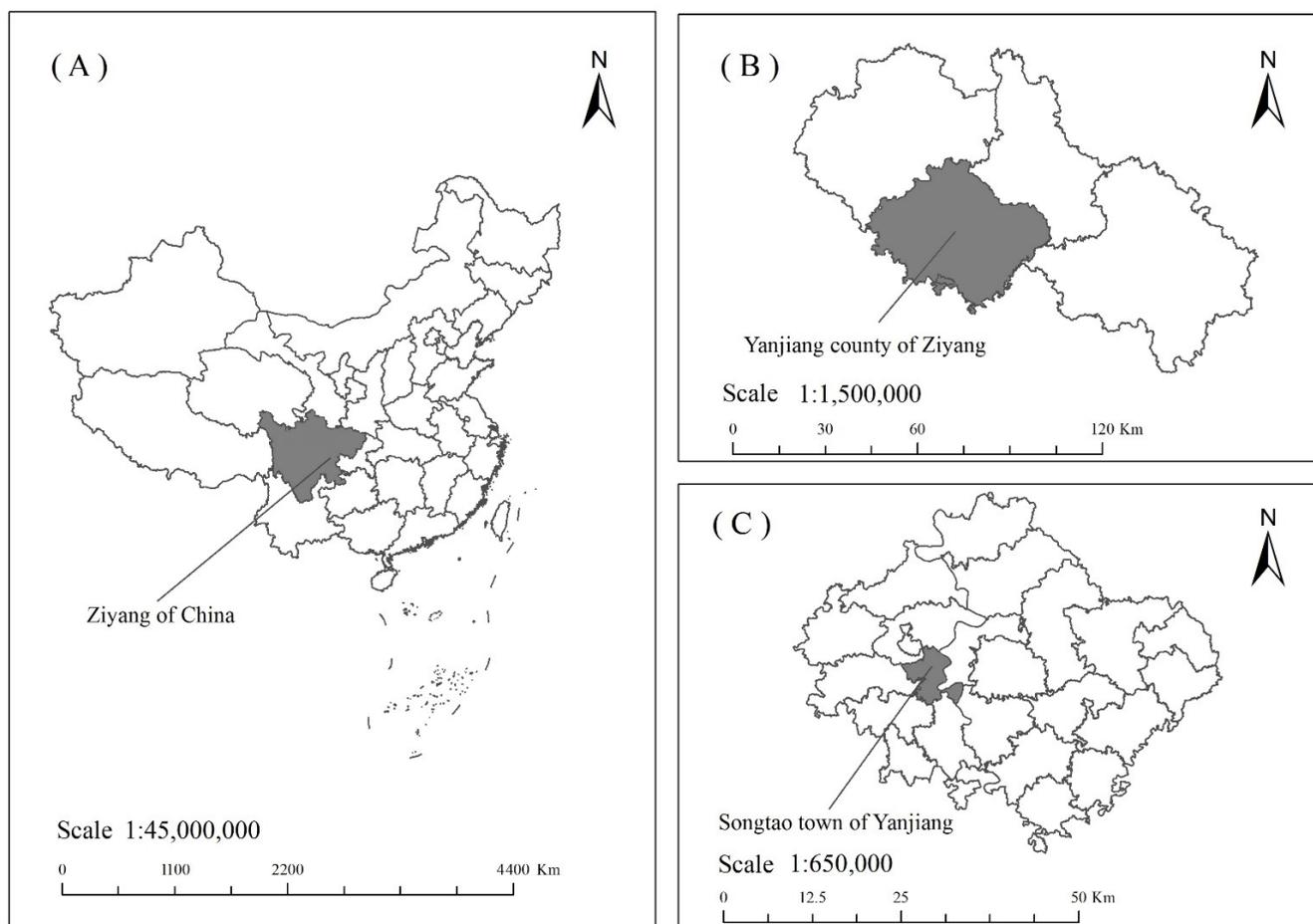


Figure 1. The location of the study area.

2.2. Leaching Experiment

Field study could give actual conditions of soil P leaching potential, but it may be limited by the experimental conditions, and the results are not easy to be interpreted because of nonlinear effects of multiple factors. It is thus necessary to use simple, reliable laboratory experiments to evaluate the risk of soil P leaching potential. Soil columns allow us to control parameters such as temperature and water content and thus facilitate investigating the impacts of fertilization rates and timing on P with other parameters under control. Furthermore, it is easy to obtain P profiles and leaching solutions at different times to give the dynamic processes.

The soil column has a size of 55 cm in height and 5.3 cm for an inner diameter (Figure 2) made of polyvinyl chloride (PVC/pipe). The P fertilizer application rates had six levels of 0 (P0), 20 (P1), 40 (P2), 100 (P3), 200 (P4), and 400 (P5) mg kg^{-1} with three replications for each level. Each column was filled with soils to 40 cm thick, but three layers were set up for each column to simulate the bulk density of 1.41 g cm^{-3} (0–10 cm), 1.44 g cm^{-3} (10–20 cm), and 1.6 g cm^{-3} (20–40 cm), respectively. The inorganic P fertilizer KH_2PO_4 was dissolved in distilled water and sprayed on the collected 0–10 cm soil samples. The soil samples with P fertilizer were placed on the top of the soil column with a 5 cm thickness, and the untreated soil was used to fill the rest of the column (i.e., 5–40 cm). Before filling, the inner wall of the column was coated with a layer of petroleum jelly to seal the gap between the soil and column. The bottom of the soil column was packed with acid-washed quartz sand and two layers of filter paper to obtain clear leachate. After filling the columns, a layer of 5 cm quartz sand was placed on the top to avoid disturbances when applying deionized water.

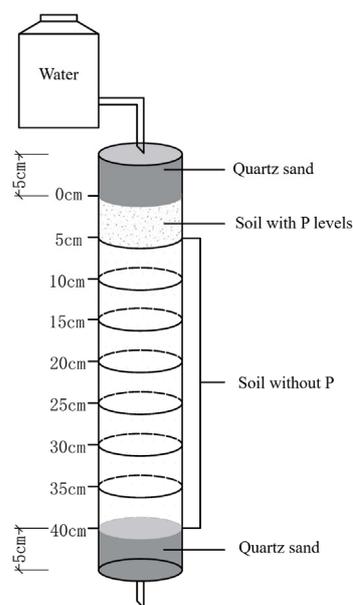


Figure 2. Schematic diagram of soil column.

To study the response of CP to different incubation times after fertilization, the soil columns were incubated after the column was filled for 7 days (T1), 14 days (T2), 21 days (T3), 28 days (T4), and 56 days (T5). Each soil column was irrigated by deionized water of 650 mL at a rate of 1.5 mm min^{-1} , and the leachate was collected into a glass bottle. As each treatment was repeated three times, a total of 90 soil columns were used. After the leaching experiment, the soil columns were dried at room temperature for 48 h to obtain soil samples of different layers with an interval of 5 cm (i.e., 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, and 35–40 cm). The leachate solution and soil samples for each treatment were analyzed to obtain the P contents of different forms.

2.3. Leachate and Soil Analysis

TP in the leach solution was digested with acidic potassium persulfate ($121 \text{ }^\circ\text{C}$, 30 min) and determined. The P forms were further defined and separated based on previous studies [12,15,17], i.e., CP ($2 \text{ }\mu\text{m} > \text{diameter} > 0.1 \text{ }\mu\text{m}$), Dissolved Phosphorus (DP) (diameter $< 0.1 \text{ }\mu\text{m}$), and Particulate Phosphorus (PP) (diameter $> 2 \text{ }\mu\text{m}$). The mixture of CP and DP was obtained after the liquid was digested with acidic potassium persulfate at $121 \text{ }^\circ\text{C}$ for 30 min through a $2 \text{ }\mu\text{m}$ microporous membrane, while the other part of the leachate was filtered through $0.1 \text{ }\mu\text{m}$ microporous membranes and the DP was obtained after the liquid was digested at $121 \text{ }^\circ\text{C}$ for 30 min with acidic potassium persulfate [15]. TP concentration minus DP concentration indicated CP concentration. The concentration of PP was calculated as the difference in concentration between TP and P through $2 \text{ }\mu\text{m}$ microporous membranes.

To extract soil colloids, 10 g of air-dried soil was mixed with 80 mL of deionized water at $25 \text{ }^\circ\text{C}$ and shaken for 24 h. The extract was centrifuged at $3000 \times g$ for 10 min and passed through a $2 \text{ }\mu\text{m}$ microporous membrane, which was defined as a colloid [18]. The determination of CP and DP concentrations in the soil solution was the same as that in the leachate.

The physicochemical properties of soil samples from different layers were measured. The organic matter (SOM) was measured by the dichromate method, the total nitrogen (TN) and available nitrogen (AN) were measured with Kjeldahl method, and the total potassium (TK) and available potassium (AK) were analyzed by flame photometry. Soil pH was measured by potentiometry in a 1:2.5 solid/water suspension. The total phosphorus (TP) and available phosphorus (AP) were measured by the colorimetric method [19].

2.4. Statistical Analysis

The analysis of variance (ANOVA) was adopted to test the significance of differences in multiple experimental setups, and a multiple comparison of means was performed using Duncan's procedure. We conducted a multiple linear regression to relate P concentrations to pH, soil depth, fertilizer application rate and incubation time. The level of significance test was defined as $p < 0.05$.

3. Results

3.1. P Concentration, pH and Volume of Leachates

In the leachate, the concentrations of TP, CP, DP, and PP increased with increasing P application rates, but they decreased with extended incubation time (Figure 3a). Overall, TP concentration in the leachate ranged from 0.01 to 0.41 mg L⁻¹ with an average of 0.12 mg L⁻¹. However, the TP concentrations have great differences between treatments of incubation times, and the five treatments of incubation time can be classified into two groups, i.e., T1–T2 and T3–T5. First, the TP concentrations of T1–T2 were 1.3 to 22.8 times of T3–T5, since the values of former and latter group were 0.08–0.41 and 0.01–0.11 mg L⁻¹, respectively. Second, the TP concentrations increased significantly ($p < 0.05$) with increasing P application rates at T1 and T2 events, but they showed little change with P application rates for T3–T5.

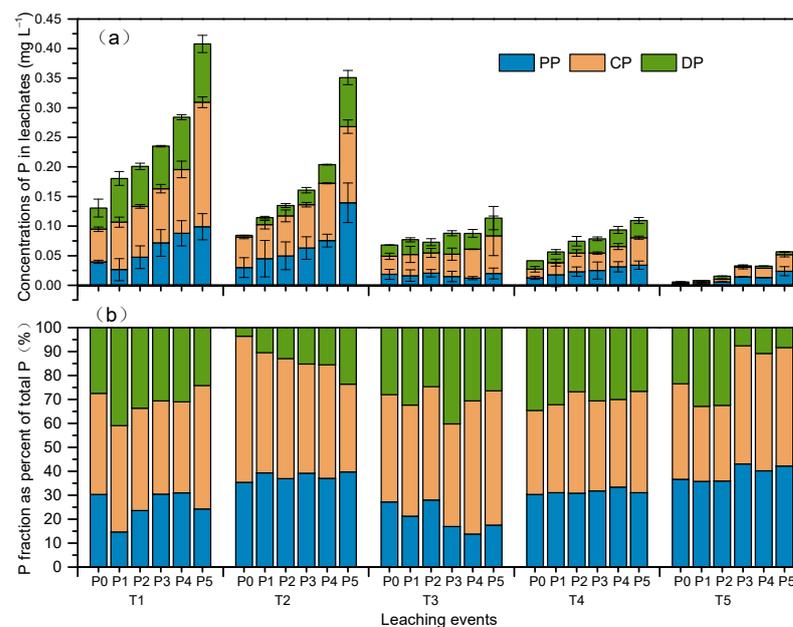


Figure 3. Phosphorus (P) concentrations in leachates (a) and P fraction as percent of total P (b) at different treatments. Phosphorus fertilizer levels at 0 (P0), 20 (P1), 40 (P2), 100 (P3), 200 (P4), and 400 (P5) mg kg⁻¹, respectively, and the soil columns were conducted at 7 days (T1), 14 days (T2), 21 days (T3), 28 days (T4), and 56 days (T5).

For different forms of P, CP concentration ranged from 0.002 to 0.21 mg L⁻¹ with an average of 0.05 mg L⁻¹, and CP contributed 31–61% to TP leaching (Figure 3b). PP concentration had a range of 0.002–0.14 mg L⁻¹ with an average of 0.04 mg L⁻¹, contributing 14–43% to TP leaching. DP concentration ranged 0.001–0.099 mg L⁻¹ with an average of 0.03 mg L⁻¹ contributing between 4% and 41% to TP leaching. It appeared that CP had the greatest concentration and contribution to TP in leachate.

The pH values of leachates for all treatments ranged 6.78–8.42 (Figure 4a) and decreased with the extended incubation time, but there was no significant difference between different P levels. The pH values in T1 were significantly higher than in T5 ($p < 0.05$), but there was no significant difference among other incubation times. The incubation time, rather than P application levels, played a more important role ($R^2 = 0.52$) on leachate pH.

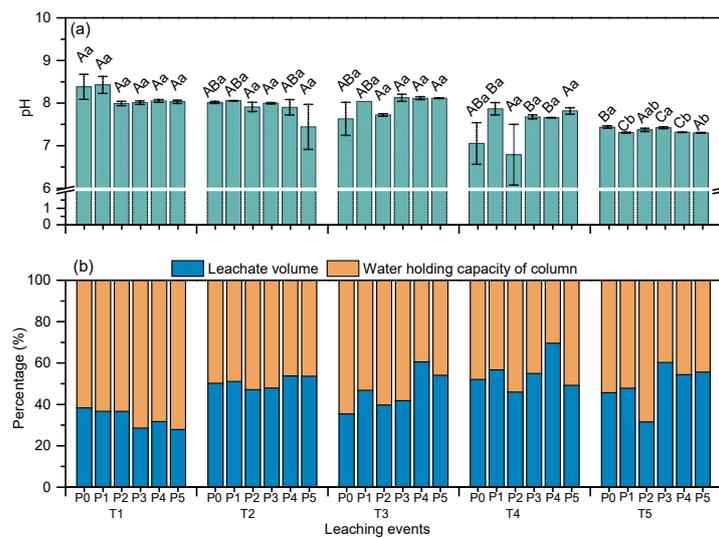


Figure 4. pH in leachate (a) and the percentage of leachate and water-holding capacity (b) at different treatments. Phosphorus fertilizer levels at 0 (P0), 20 (P1), 40 (P2), 100 (P3), 200 (P4), and 400 (P5) mg kg^{-1} , respectively, and the soil columns were conducted at 7 days (T1), 14 days (T2), 21 days (T3), 28 days (T4), and 56 days (T5). Different capital letters above the bars indicate significant differences among different times ($p < 0.05$). Different lowercase above the bars indicate significant differences among different P levels ($p < 0.05$).

The volume of leachate from different P application levels fluctuated with incubation time (Figure 4b). The volume of leachate for T1 was significantly lower than that for T2–T5, but there was no significant difference in the volume of leachate for T2–T5. For P application levels, the leachate volumes of P3–P5 were greater than those of P0–P2. We note that the longer the incubation time, the larger amount of water infiltration in the soil.

3.2. Concentration of Phosphorus in Soil Profiles

CP and DP concentrations decreased significantly with the increase in soil depth (Figure 5), and their values in the 0–10 cm range were significantly larger than in other layers (Figure 5a). The average CP and DP concentrations of whole columns in P0–P3 were significantly lower than those in P4–P5 ($p < 0.05$). The highest CP concentration (8.10 mg kg^{-1}) was found in 0–5 cm soil layer at T4 of P5 treatment. The CP concentrations after P addition (P1–P5) in the 0–5 cm depth were 2.1–13.4, 2.6–11.1, 1.2–10.0, 1.6–12.2, and 1.9–11.8 times greater than that those of P0 at T1, T2, T3, T4, and T5, respectively. However, there was no significant difference in the CP concentrations of same P level between different incubation times.

The DP concentrations in the 0–5 cm soil layer increased with increasing P application levels at the periods T1 to T5. The DP concentrations after P addition (P1–P5) were 6.1–215.2, 4.1–72.0, 4.6–125.4, 17.1–229.8, and 1.7–44.0 times of those for P0 at T1, T2, T3, T4, and T5, respectively (Figure 5b). However, the DP concentrations of P1, P2, P4, and P5 in the 0–5 cm layer were the highest (about 1.80, 4.43, 16.51, and 31.52 mg kg^{-1} , respectively) at T2. DP concentration in P3 showed no significant differences between incubation times. Furthermore, there was no difference in DP concentrations between the P1, P2 treatment and P0 treatments at T5. We found that there were different effects on the P distribution in the soil profile with the different P application rates. The soil P concentrations in the 0–15 cm soil layer were significantly higher than that in the 15–40 cm soil layer under different P rates, and there was no significant difference in P concentration in the 15–40 cm soil layer. DP concentrations were higher than CP concentrations in soil profiles of our different treatments. Compared to P0 treatment, P treatment makes DP more readily released from soil than CP.

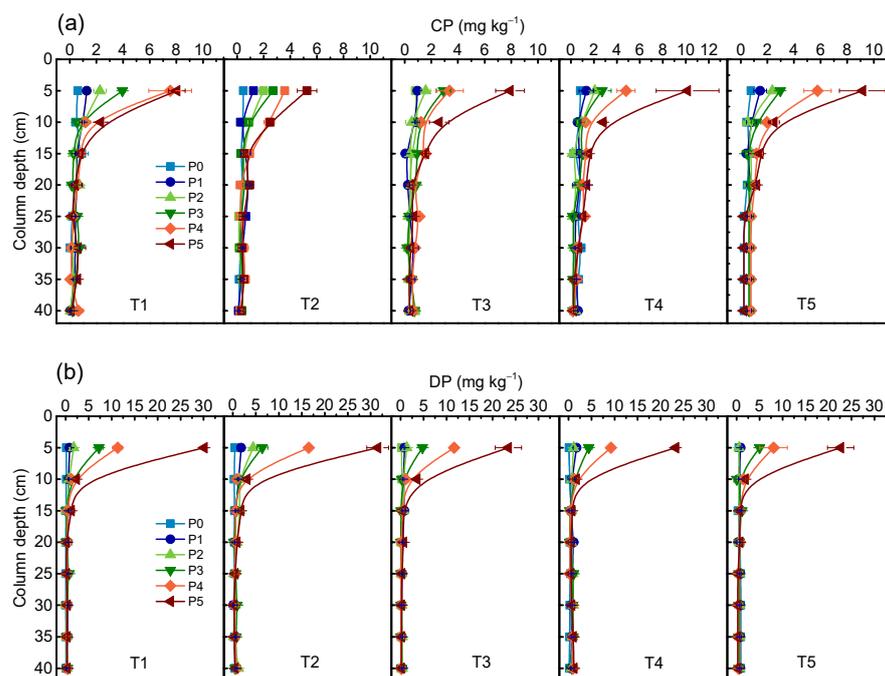


Figure 5. Distribution of colloidal phosphorus (CP) (a) and dissolved phosphorus (DP) (b) in soil profiles at different treatments. Phosphorus fertilizer levels at 0 (P0), 20 (P1), 40 (P2), 100 (P3), 200 (P4), and 400 (P5) mg kg⁻¹, respectively, and the soil columns were conducted at 7 days (T1), 14 days (T2), 21 days (T3), 28 days (T4), and 56 days (T5).

4. Discussion

4.1. Whether Phosphorus Leaching Loss after Fertilization Is a Risk to Water Bodies?

Increasing studies have shown that P concentrations in underground drainage systems are high enough to cause water quality to deteriorate [11,20]. The application of P can increase soil surface and underground P concentration [2]. The high P saturation in soil triggered the soil colloid's dispersion due to high P concentration, which released more CP [21,22]. In this study, all P forms increased with increasing P fertilizer rates. The TP concentration in leachate ranged from 0.01 to 0.41 mg L⁻¹ with an average of 0.12 mg L⁻¹, and the DP concentration in leachate ranged from 0.001 to 0.099 mg L⁻¹ with an average of 0.03 mg L⁻¹ (Figure 3). Christophe et al. reported that the laboratory column experiments showed that TP concentrations ranged 0.05–0.132 mg L⁻¹ in the leachate of paddy soil [11]. Similarly, Jalali et al. conducted a column leaching experiment and reported that the P concentration in leachate was smaller than 0.2 mg L⁻¹ in native soil during 45 days of leaching [23]. According to USEPA [24], the TP concentration of 0.05–0.10 mg L⁻¹ can be used as a threshold for surface water eutrophication. The eutrophication of flowing waters can be caused by P discharge in excess of 0.1 mg TP L⁻¹ and 0.01 mg DP L⁻¹; however, this limit can be readily exceeded in areas with fertilizer application [25]. Accordingly, in this study, 43% of TP from leaching experiments exceeded the threshold, mainly in T1–T2 under different P fertilization levels and all the leaching events of P5. Furthermore, most of the DP concentrations were >0.01 mg L⁻¹ (77%) except for the DP concentrations of T5 for all P treatments, which were <0.01 mg L⁻¹. There is no doubt that the application of P fertilizer increases the soil P concentration, which also mainly depends on the type of P fertilizer. Fresne et al. concluded that the application of organic P had no effect on the medium-sized (200–450 nm) CP concentration, even though the proportion of organic P application was higher than that of synthetic fertilizer treatment [26]. However, in our study, the application of P fertilizer had a significant effect on soil P concentration, especially in the topsoil.

In conclusion, the longer the soil culture time with phosphorus application, the stronger the adsorption capacity of P in the soil. The risk of P leaching loss was greater in the first 14 days after P application, and the risk was greater when P application rates

were $>200 \text{ mg kg}^{-1}$. Jalali et al. reported that the relatively high initial concentration of P in the leachate decreased to stable values after 10 days [23]. Shan et al. indicated that the peak of P leaching loss occurred within 10 days after fertilization in paddy soil under flooded conditions [27]. We concluded that the peak of P leaching loss occurred within two weeks after fertilization in dryland soils. There was no flooding on the soil surface, and the P retention time in the soil was longer. The adsorption effect of soil on P in the upper soil increases with extended incubation time [1]. On the other hand, the leaching solution from the soil columns was turbid at T1, which was mainly due to the severe internal erosion in the macropores that caused fine particles to flow out with the water [28].

The risk of leaching loss of P is mainly within one month after P application, especially within two weeks, which is the period with high risk from P leaching. If there is rainfall or irrigation during these two weeks, more P in the soil will be lost in solution. Therefore, the initial leaching events can have large impacts on P loss to pose a high potential environmental risk. Furthermore, in order to avoid excessive loss of P via leaching, the advisable range of P application is recommended to be $<200 \text{ mg kg}^{-1}$, and we suggest that the amount of P fertilizer should be controlled within 450 kg ha^{-1} for agricultural practice.

4.2. How Important Is Colloidal Phosphorus (CP) in Phosphorus Leaching Loss?

CP is known to encourage blue–green algal blooms and accelerate water eutrophication rates [10], and it can be easily leached from the soil and remain in solution for a long period [9,29]. The concentrations of CP leaching in P1–P5 were higher than those unfertilized (P0) (Figure 3) with an increase of 24–375%. Christophe et al. reported that the CP concentration ranged $0.002\text{--}0.03 \text{ mg L}^{-1}$, accounting for 3–26% of TP [11]. Other studies showed that compared with unfertilized soils, the amount of CP migration in fertilized soil generally increased by $>25\%$ [17]. In our study, CP, PP and DP contributed 31–61%, 14–43% and 4–41% to TP leaching, respectively. CP was the dominant fraction in P leachates.

The concentrations of CP and DP in 0–10 cm layers were significantly higher than those of other layers (Figure 5) and decreased significantly with depths ($p < 0.05$). These results are similar as those reported by [14]. Calcareous soil is rich in minerals such as calcium and magnesium from soluble calcium, with magnesium and P mineral complexes on the surface controlling P solubility [30]. The formation of these minerals significantly reduces the activity of P in soil solution and the leaching potential [31]. Large concentrations of DP were fixed in the layers of 0–10 cm in our study. These results were similar to those of Sharma et al., who reported that the P fertilizer application increased soil DP concentration at depths of 0–5 and 5–10 cm but weakly at 10–15 cm [32]. This was mainly attributed to the increasing culture time after P application, enhanced adsorption of P in soil, and decreased release of P under water flow [33].

4.3. Impact Factors of Colloidal Phosphorus during Leaching Events

It is reported that the transportation of CP was strongly affected by pH. Specifically, changes of pH can drive the release of colloids, and the amount of colloid particles released from water-bearing media increases with increasing pH [17,34,35]. There was a positive significant nonlinear correlation between pH and P concentration in leachate (Figure 6). Furthermore, pH can explain the variation of TP, CP, DP and PP by 31%, 34%, 17%, and 27%, respectively. Thus, pH is a good predictor of CP in this study. Similar results have been reported by previous studies [11].

The other important factor influencing P loss is the contribution of P in topsoil. Fertilization significantly affects the P content in surface soil [1]. In this study, P fertilizer application significantly increased CP concentrations in 0–15 cm and DP concentrations in 0–10 cm but had minor effects on the concentrations at deeper layers (Table 2). The penetration depth of CP was greater than that of DP after P application, suggesting that CP has a greater transport ability than DP in the soil profile. This may be because our calcareous soils were rich in Ca^{2+} . Christophe et al. found there were significant positive correlations between CP and colloidal calcium (Ca_{coll}), and Ca minerals–organic matter

may play a major role as a carrier for CP in solution [11]. In general, the fate of P in agricultural soils depends not only on the presence of P in soil solution but also on CP migration [36,37].

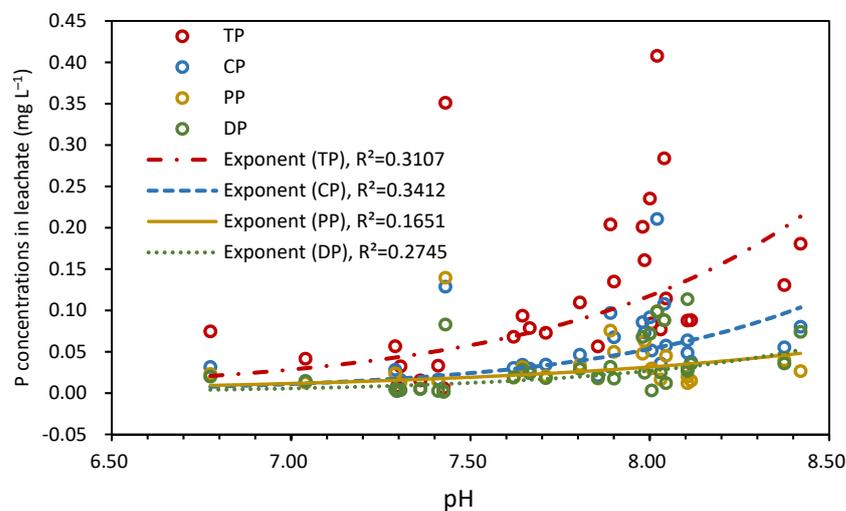


Figure 6. Relationship between total phosphorus (TP), colloidal phosphorus (CP), dissolved phosphorus (DP), and particle phosphorus (PP) in leachate and pH. Curves represent fits of nonlinearity model to the data. All fitted lines are significant at the $p < 0.01$ level.

Table 2. Coefficient of determination (R^2) for the relationship between the phosphorus (P) application rates and colloidal phosphorus (CP) and dissolved phosphorus (DP) of different soil layers.

Soil Layers (cm)	Correlation Coefficients (R^2) for P Application Rates with	
	CP	DP
0–5	0.8751 **	0.9491 **
5–10	0.8406 **	0.7241 **
10–15	0.4611 *	0.1231
15–20	0.1158	0.0688
20–25	0.1489	0.0287
25–30	0.0863	0.0479
30–35	0.0081	0.0244
35–40	0.0912	0.0082

Note: ** and * represent $p < 0.01$ and $p < 0.05$, respectively.

The P application tends to increase water infiltration through reducing soil bulk density and increasing soil porosity [38]. The increasing infiltration will inevitably lead to more P leaching loss [39]. There were significant correlations between P concentration in leachate and P application rates, which could be described by binomial expression (Figure 7). The P levels were found to account for >92%, >85%, >68%, and >31% of the variation in TP, CP, PP, and DP in leaching, respectively. Thus, P application has a great effect on TP and CP in leaching because of the significant increase in surface soil P concentrations (Table 2).

Heckrath et al. found a linear correlation between P concentrations in subsurface drainage (65 cm deep) and P application rates in surface soils (0–23 cm) in a dryland fertilization experiment from the Broadbalk Experiment at Rothamsted [40]. We found that P concentrations in leachates changed little at T3–T5 with increasing P application rates (Figure 7). The concentration of P was higher at the beginning of the leaching experiment and decreased with the time (Figure 3). The stability of P in soil increases with cultivation time, which was probably because P fertilizer was applied to the topsoil to result in higher P concentrations in upper soil. In addition, the concentration of different P forms in leachates decreased significantly over time (Figure 3). Culture time affected soil properties, including the internal structure of soil (large pores or cracks appear), and the presence of large

pores. The increased volume of the leachate will dilute the limited P, resulting in a lower P concentration (Figure 3). Rapid water movement through coarse textured soil and short culture time (when 14 days in this study) for P desorption results in high P leaching [2,41,42]. The P application and culture time in soil may constitute an important CP transport and release mechanism in the soil leaching process. P concentrations in the soil profile decreased with increasing soil depths (Figure 5). The CP concentrations of the soil profile showed a power–function relationship with increasing soil depths ($y = 14.481x - 1.031$, $R^2 = 0.9607$, $p < 0.01$). The shallower the soil layer, the higher the soil CP concentrations. There was no significant difference in soil CP concentrations at the bottom of soil columns, and as previously mentioned, the P fertilizer application mainly affected the CP concentrations of the upper soil. There was a highly significant linear relationship between the CP concentration in surface soil and leachate ($y = 0.0081x + 0.0263$, $R^2 = 0.9757$, $p < 0.01$). The higher the CP concentration in the soil, the higher the CP concentration in the leachate. In situations where it is difficult to sample groundwater, we can predict the CP concentration in the leachate with the developed functions. The influence of CP on the environment is different from that of DP and PP, which is mainly determined by the special characteristics of colloid [11]. The true composition of CP needs further study and colloidal minerals in soils to better predict the mobility of CP, availability for biological uptake, and sorption on reactive surfaces.

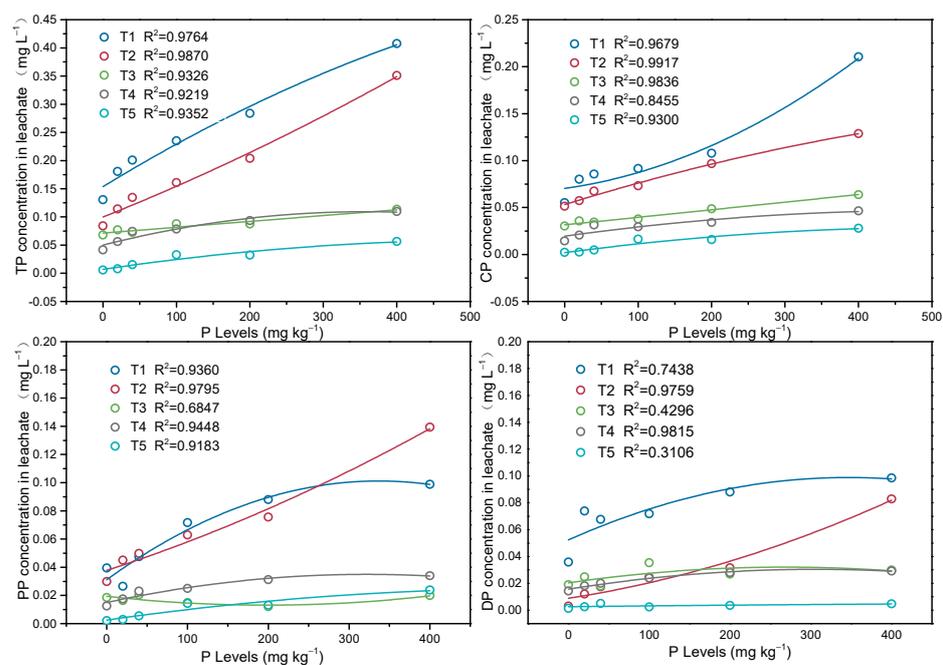


Figure 7. The relationship between total phosphorus (TP), colloidal phosphorus (CP), dissolved phosphorus (DP), and particle phosphorus (PP) in leachate and phosphorus (P) application levels after the soil columns were conducted at 7 days (T1), 14 days (T2), 21 days (T3), 28 days (T4), and 56 days (T5).

5. Conclusions

The concentrations of P in the leachate of purple soil increased with increasing P application and decreased with increasing incubation time. CP was predominant in the loss of P in the leachate, and it has a stronger migration ability than dissolved phosphorus (DP). P application had a large effect on CP and DP concentrations in the 0–10 cm soil layer, and the degree of effect decreased significantly with the increase in soil depth. The purple soil has a greater potential of P leaching loss under P fertilization with a potential increase of 24–375% after P application. The TP concentration in the leachates was above the critical level of 0.1 mg L^{-1} when the P application is $>200 \text{ mg kg}^{-1}$ or within two weeks after fertilization. P application and incubation time in soil may be an important mechanism

controlling CP transport and release during soil leaching events. Therefore, some measures should be adopted to minimize the buildup of P in the field, and great management efforts should be made for soils with a high risk of P leaching. The advisable range of P application rate is recommended to be 0–450 kg ha⁻¹ for agricultural practice and keeping P fertilizer in the soil for more than two weeks.

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