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Environmental Threshold of Phosphorus Infiltration in Red Soil under Different Land Use Patterns

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Abstract

The risk of soil phosphorus leaching increases in basin regions in light of large-scale use of phosphorus fertilizers because of agricultural modernization. In this study, we conducted an earth pillar simulation test on the infiltration threshold of red soil, Vaseline-coated PVC pipe, intact soil core, fine sand, and nylon filter was used for Penetration test, which covers the largest area of the Dianchi Lake Basin in China. Results showed that: 1) The contents of the total available phosphorus in algae (NaOH-P) and dissolved labile phosphorus ($CaCl_2$-P) in red soil were consistent with the content of available phosphorus (Olsen-P) under different use patterns manifested by the law of greenhouse > open field > grassland. Grassland had the highest phosphorus sorption index (PSI), followed by the greenhouse and then by the open field. 2) The leachate under the same use pattern had the characteristics of total phosphorus (TP) > particle phosphorus (PP) > total dissolved phosphorus (TDP) > dissolved organic phosphorus (DOP) > molybdate reactive phosphorus (MRP). The TP contents in the leachates of grassland, greenhouse, and open field were 0.46, 0.61, and 0.49 mg/L, respectively. DOP, TDP, PP, and MRP had similar contents, and their distributions in the three land types were consistent with that of TP. 3) Olsen-P had a significant correlation with TP, TDP, PP, and DOP in the leachates. Olsen-P of <40 mg/kg and PSI of >50 slightly influenced eutrophication. Moreover, Olsen-P of >40 and <70.90 mg/kg and PSI of >40 had minimal influence on the environment. Olsen-P of >70.90 mg/kg and PSI of <30 significantly influenced eutrophication in Dianchi Lake Basin. 4) When Olsen-P was >26.09 mg/kg, the TP content in the leachate increased sharply.

Keywords

Environmental Threshold, Leachate, Phosphorus, Red Soil

1. Introduction

Water eutrophication has become a serious concern worldwide. Phosphorus (P) is an essential nutrient element. The C:N:P ratio in water biology is generally 105:15:1, indicating the far lower demands for P in water biology compared with those for carbon and nitrogen. Approximately 20 - 35 μg/L can cause water eutrophication. Therefore, P is generally used as one constraint of water eutrophication (Liu et al., 2021; Xu et al., 2016; Liu et al., 2020).

Fertilizers containing P are increasingly used to boost crop yields. As P cannot easily migrate in soil, it continuously accumulates in the soil surface. Consequently, when P content in soil reaches a certain level, it starts to considerably affect the local environment (Rashmi et al., 2020). P content in water mainly originates from agricultural nonpoint source pollution of P drainage from farmlands with improving point-source pollution management (Qiu et al., 2011; Hao et al., 2013; Zheng et al., 2016; Li et al., 2021; Shan et al., 2004). The application of P fertilizers continues to increase because of the changes in the agricultural and industrial structures in Dianchi Lake Basin. The continuous application of P fertilizers increases the risks of P loss in soil and damages to the water environment. Moreover, the expansion of the greenhouse area reduces runoff losses and increases the possibility of damages because of leakage. Meanwhile, although water eutrophication control in the basin has achieved a significant effect, the environmental threshold of soil P in the study area remains unclear. (Heckrath et al., 1995) studied the "mutational site" of soil P leaching in a long-term soil fertilizer experimental field located at Rothamsted Experimental Station (UK). They formulated a correlation curve by using Olsen-P content as x-axis and -P content as y-axis and detected P leaching at Olsen-P of >60 mg/kg. Lv et al. achieved similar results when they formulate a correlation curve between molybdate reactive phosphorus (MRP) and Olsen-P in the same experimental field, indicating that the risk assessment on the environmental threshold of soil P is variable (Liu et al., 2020; Lv et al., 2003). (Li et al., 2016) made a risk assessment on P in dry yellow earth, which has been subjected to long-term fertilization in the center of Guizhou, and they found that P in dryland considerably affects water environment quality when Olsen-P is >40 mg/kg and soil P saturation is >5% (Guan et al., 2018).

In the present study, Dianchi Lake Basin soil samples subjected to different land-use patterns were collected, and the basic properties and different forms of P were tested. In particular, a soil pillar simulation test was conducted to examine the different forms of P contents in leachates. The environmental threshold of P in the basin was evaluated through correlation curves and clustering analysis to obtain an accurate value that can be used as reference for water eutrophication control and agricultural scientific application of phosphate fertilizers.

2. Materials and Methods

2.1. Study Area

Dianchi Lake, the largest freshwater lake in southwest China, is located in the southwestern part of Kunming, Yunnan Province (China) and belongs to the Jinsha River system. The Dianchi Lake Basin has a mid-subtropical humid monsoon climate. The annual average rainfall is approximately 1000 mm, and rainfall mainly concentrates from May to October. Covering an area of 2920 km^2, this basin plays an important role in the economic and social development of Kunming City. However, owing to economic development, the agricultural and industrial structures in the basin continue to change. In particular, a single agricultural plantation causes unreasonable fertilization, and severe soil erosion caused by P mining in the west and southwest of the basin further intensifies P loss. Moreover, the unreasonable drainage of domestic wastewater of people renders water eutrophication control in Dianchi Lake increasingly difficult.

2.2. Test Soil Samples

Different red soil samples from different layers of the three land-use patterns in the study area were collected (red soil in different land-use patterns has different P contents, which were mainly divided into high, middle, and low content). The major physical and chemical properties of the test soil samples are listed in Table 1. Each physical and chemical property was analyzed through the conventional soil agrochemical method. All the soil samples were air-dried and then filtered for subsequent use.

Table 1. Basic properties of the soil samples.

Land use pattern	Soil layer (cm)	pH	Organic matters OM (%)	Available nitrogen AN (mg/kg)	Available potassium AK (mg/kg)	Rapid available phosphorus AP (mg/kg)
Grassland (grassland)	0 - 20	6.30	3.80	322.11	73.68	8.33
	20 - 40	5.95	4.51	282.02	65.07	8.94
	40 - 60	5.69	4.12	256.72	77.98	8.94
Open field (open field)	0 - 20	7.55	3.64	219.00	47.85	31.72
	20 - 40	7.84	3.20	225.41	34.95	24.39
	40 - 60	7.62	3.53	138.08	22.05	11.06
Greenhouse (greenhouse)	0 - 20	7.45	5.34	56.37	1049.83	87.02
	20 - 40	6.78	5.03	28.14	1054.81	81.96
	40 - 60	7.47	3.26	46.03	688.93	67.45

2.3. Experimental Design

A piece of 60 cm-long and Vaseline-coated PVC pipe with an inner diameter of 7 cm was used. The bottom of the pipe was sealed with a piece of cotton cloth with good air permeability, and a layer of approximately 2 cm-thick quartz sand was applied. A piece of 300-mesh screen was placed on the quartz sand. The soil layers were at 0 - 20, 20 - 40, and 40 - 60 cm from the top to the bottom, and each layer was isolated by a nylon net. A small hole (diameter = 0.5 cm) was opened at the bottom of the soil column, which was plugged by a rubber stopper to facilitate leachate collection. The soil column was placed straight on the shelf and was divided into grassland 1, grassland 2, grassland 3, greenhouse 1, greenhouse 2, greenhouse 3, open field 1, open field 2, and open field 3. Leachate was collected by a triangular flask (Yin, 2019).

The experiment was accomplished in a greenhouse. The irrigation amount (soil saturation moisture capacity) was controlled according to the field capacity by quality law. The soil samples were irrigated with approximately 275 mL of water every week. The soil samples were cultured for 1 week, and leachate was collected by a triangular flask. A total of 27 samples were obtained (three parallel test samples were obtained in each P level).

2.4. Test Items and Methods

The P indexes in soil and leachate (P indexes in leachate used the mean of four irrigations) (Yang, 2005; Xu et al., 2015; Tao, 2020; Heckrath et al., 2007; Lu, 2000) were analyzed using the following parameters:

Total available P in algae (NaOH-P) presents in soil. This parameter, which includes water-soluble P and some solid P that can be accessed by algae, was tested by 0.1 mol/L of NaOH digestion-molybdenum blue colorimetric determination (water-to-soil ratio = 1:500 and vibration time = 16 h).

Dissolved labile P ($CaCl_2$-P) in soil: This parameter was tested using 0.01 mol/L of $CaCl_2$-extracting solution (water-to-soil ratio = 1:5 and vibration time = 30 min) by isobutyl alcohol extraction-molybdenum blue colorimetric determination.

P sorption index (PSI) in soil: Given that a water-to-soil ratio is 10:1, 1.5 mg of P was added into each gram of soil sample. The PSI is the logarithm of the P sorption in soil (X, mg/g) and P concentration in a balanced solution (C, μmol/L), that is, PSI = 100 X/lg C.

Total phosphorus (TP) in leachate: (70% - 72%) 2 mL of pure perchloric acid and 0.25 mL of saturated magnesium chloride solution were added to the samples and digested until nearly dry under high temperature. Approximately 5 mL of 0.6 mol/L diluted hydrochloric acid was added and dissolved by heating. Finally, the mo-sb-vc method was adopted for the colorimetric assay.

MRP in leachate: A certain amount of filtrate screened by 0.45-um Millipore membrane was used to perform a direct colorimetric assay based on the mo-sb-vc method. The MRP was the collected P and generally composed of inorganic phosphorus.

Total dissolved phosphorus (TDP) in leachate: TDP was tested through the same method used for TP with a certain amount of filtrate screened by 0.45 μm Millipore membrane.

Dissolved organic phosphorus (DOP): Difference between TDP and MRP.

Particle phosphorus (PP): Difference between TP and TDP.

2.5. Data Processing Methods

Basic data processing was performed using Microsoft Excel, while significance variance, correlation, and clustering analysis were conducted by SPSS.

3. Results and Analysis

3.1. Contents of the Different Forms of P in the Different Land Use Patterns

As shown in Figure 1, the $CaCl_2$-P content in the grassland ranges between 0.14 and 0.32 mg/kg. Meanwhile, no significant difference was observed among the different layers in terms of mean $CaCl_2$-P content. The average of $CaCl_2$-P in 0 - 20, 20 - 40, and 40 - 60 cm layers were 0.29, 0.15, and 0.23 mg/kg, respectively. However, the $CaCl_2$-P content in the grassland was significantly different from those in the greenhouse and open field. The maximum and minimum $CaCl_2$-P contents in the greenhouse were 9.43 and 8.03 mg/kg, indicating distinctive layering features. The average $CaCl_2$-P content in the open field was significantly different from those in the grassland and open field. The maximum and minimum $CaCl_2$-P contents in the open field were 3.37 and 2.13 mg/kg, respectively. Of the three different land-use patterns, the greenhouse had the highest $CaCl_2$-P content, followed by the open field and grassland successively. This distribution trend was consistent with the AP content ($P < 0.05$).

The NaOH-P content in soil varied significantly in different land-use patterns. The mean NaOH-P contents in the grassland and open field were 62.26 and 156.36 mg/kg, respectively. No difference was observed between the NaOH-P contents in the grassland and open field as the soil depth increased, whereas the NaOH-P contents in the greenhouse decreased continuously. The NaOH-P

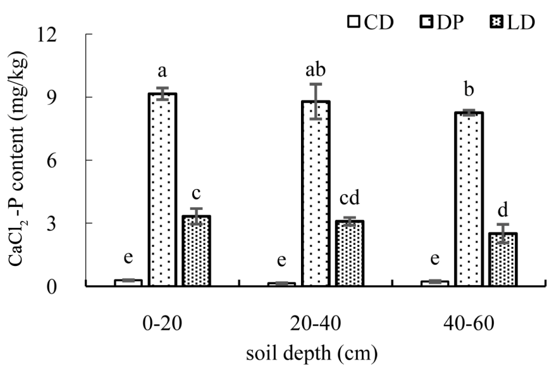

Figure 1. $CaCl_2$-P content in soil layers under different P levels (mg/kg).

contents at 0 - 20, 20 - 40, and 40 - 60 cm were 162.47, 157.08, and 149.54 mg/kg, respectively. These results indicated that soil P migrates downward. The NaOH-P content in red soil varied significantly under different land use patterns, showing the same variation trend of Olsen-P ($P < 0.05$; **Figure 2**).

In **Figure 3**, the PSIs of the soil layers in each land-use pattern generally ranged between 20 and 40 and in the following order: Grassland > open field > greenhouse. This phenomenon was related to fertilization. The PSIs of the grassland soil layers were basically consistent, thereby reflecting uniform P distribution. Consistent with the reduction of Olsen-P from the superficial to the deep layers, PSIs in the greenhouse and open field decreased gradually when soil depth increases. The PSI in the greenhouse was lower than that in the open field because of the intensive crop plantation activities throughout the year. Furthermore, PSI was closely related to soil P content and slightly reflected P loss risks.

3.2. Soil Pillar Simulation Test Results of the Land Use Patterns

The averages of the TP contents in the leachates of grassland, greenhouse, and open field were 0.46, 0.61, and 0.49 mg/L, respectively, showing a distribution trend in the order of greenhouse > open field and grassland. No significant difference was observed. TDP was tested from the leachate filtered by a 0.45 μm Millipore membrane. The average TP content of the test groups in the grassland

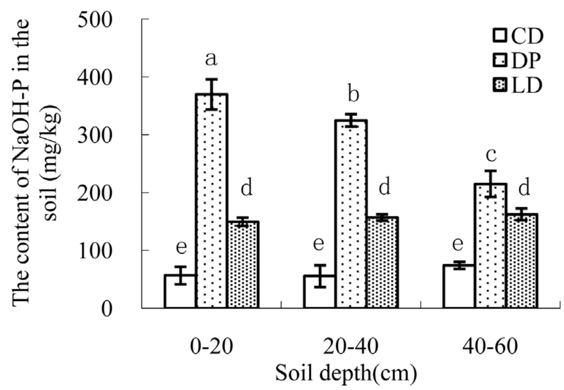

Figure 2. NaOH-P contents of different soil layers with different P contents (mg/kg).

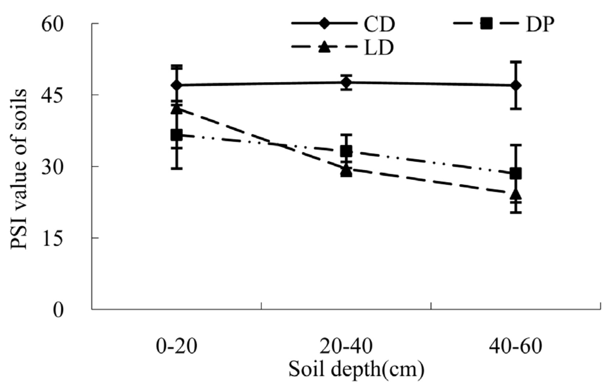

Figure 3. PSI of soil layers under different P levels.

was 0.26 mg/L, which was approximate to that of the test groups in the open field (0.28 mg/L). The average TP content in the greenhouse was 0.35 mg/L, which was slightly higher than those in the grassland and open field. Meanwhile, the average MRP contents in the leachates of the grassland and open field were both 0.14 mg/L, which is slightly lower than that in the greenhouse (0.17 mg/L). The PP in the soil leachate of the greenhouse reached a maximum value of 0.38 mg/L, which was higher than those in the open field (0.28 mg/L) and grassland (0.19 mg/L). The highest DOP content (0.27 mg/L) was observed in the soil leachate of the greenhouse, in which the average DOP value was 0.18 mg/L. Meanwhile, the averages of the DOP contents in the grassland and open field were both 0.13 mg/L. The lowest DOP content (0.076 mg/L) was obtained in the soil leachate of the grassland (Table 2).

Table 2. P indexes in leachate (mg/L).

Sample size		TP	TDP	MRP	PP	DOP
1	Grassland 1	0.5682	0.3251	0.1860	0.2431	0.1391
2		0.5250	0.3231	0.1946	0.2020	0.1285
3		0.5574	0.3124	0.1894	0.2450	0.1230
4	Grassland 2	0.4386	0.3082	0.1469	0.1304	0.1613
5		0.3974	0.2808	0.1270	0.1166	0.1538
6		0.3482	0.2146	0.1383	0.1336	0.0763
7	Grassland 3	0.4611	0.2858	0.1192	0.1753	0.1666
8		0.3978	0.1759	0.0682	0.2219	0.1078
9		0.4414	0.1579	0.0827	0.2835	0.0752
10	Greenhouse 1	0.6117	0.2782	0.0661	0.3334	0.2121
11		0.4934	0.2471	0.1155	0.2463	0.1316
12		0.4599	0.1979	0.1261	0.2620	0.0718
13	Greenhouse 2	0.6288	0.4009	0.1547	0.2279	0.2463
14		0.7177	0.3812	0.2277	0.3365	0.1534
15		0.7465	0.3715	0.1643	0.3750	0.2073
16	Greenhouse 3	0.6542	0.4140	0.1780	0.2402	0.2360
17		0.5272	0.3904	0.2671	0.1367	0.1233
18		0.6163	0.4805	0.2134	0.3563	0.2671
19	Open field 1	0.5885	0.3436	0.1977	0.2450	0.1459
20		0.5855	0.2687	0.1494	0.3168	0.1193
21		0.4146	0.2588	0.1567	0.1558	0.1021
22	Open field 2	0.5167	0.2931	0.1268	0.2237	0.1663
23		0.5652	0.2823	0.1376	0.2830	0.1446
24		0.4931	0.2471	0.1293	0.2460	0.1177
25	Open field 3	0.4083	0.3031	0.1363	0.1051	0.1668
26		0.3624	0.2451	0.0973	0.1173	0.1478
27		0.4410	0.2471	0.1470	0.1939	0.1000

Significant differences were observed among the soil leachates of the three different land-use patterns with respect to TP and PP. The trends in these parameters were in the following order: Greenhouse > open field > grassland. This trend was also observed in the AP values in soils. By contrast, the MRP and TDP contents were similar. However, the MRP and TDP contents in the three land-use patterns varied considerably, and their trends followed the order of greenhouse > open field > grassland. The DOP content had no significant difference ($P < 0.05$). At the same land use pattern, the PP content in the leachate is the highest, followed by TDP, DOP, and MRP successively.

3.3. Correlation Analysis between Olsen-P and Different Forms of *P*

The bilateral correlation between the Olsen-P in red soil and different forms of P in leachates were determined using statistical analysis performed in SPSS. The results showed significant correlation of Olsen-P in soil with the mean values of TP, TDP, PP, and DOP in the four tests. The correlations are illustrated in Figure 4. MRP was neglected.

In Figure 4, TP = 0.0021 Olsen-P + 0.4411 (R = 0.6269), TDP = 0.001 Olsen-P + 0.2607 (R = 0.6622), PP = 0.0013 Olsen-P + 0.1788 (R = 0.5518), and DOP = 0.001 Olsen-P + 0.2607 (R = 0.5864).

Soil samples were divided into four types (Table 3) on the basis of the SPSS-based clustering analysis results on the different forms of P in soil samples and leachates (Figure 5).

In Table 3, the red soil samples of each land use pattern were divided into the following types through clustering analysis: 1) Olsen-P content ranged between 8.27 and 11.55 mg/kg, including all types of grasslands and some open fields with low Olsen-P content. 2) Olsen-P content ranged between 23 and 33.45 mg/kg, including all open fields excluded from the first type. 3) Olsen-P content ranged between 65.45 and 68.54 mg/kg, including the three testing groups in the greenhouse. 4) Olsen-P content ranged between 80.28 and 94.35 mg/kg, including the remaining six testing groups in the greenhouse. The TP content in the water in Dianchi Lake Basin reached approximately 0.59 mg/L. Olsen-P content in soil was higher than 70.90 mg/kg in TP = 0.0021 Olsen-P + 0.4411 (R = 0.6269). Based on these types, Olsen-P of <40 mg/kg and PSI of >50 had no influence on the water eutrophication in the Dianchi Lake Basin. However, Olsen-P

Table 3. Clustering analysis results of red soil samples and leachates.

Category	P in soil (mg/kg)				P in leachates (mg/L)			
	Olsen-P	NaOH-P	$CaCl_2$-P	PSI	TP	TDP	PP	DOP
n = 12	8.27 - 11.55	41.14 - 168.47	0.14 - 2.99	42.48 - 52.68	0.35 - 0.57	0.16 - 0.33	0.14 - 0.19	0.1 - 0.17
n = 6	23 - 33.45	144.26 - 162.82	2.9 - 3.73	30.26 - 49.74	0.42 - 0.59	0.25 - 0.34	0.13 - 0.20	0.12 - 0.17
n = 3	65.45 - 68.54	189.74 - 232.91	8.17 - 8.4	28.41 - 34.59	0.53 - 0.65	0.39 - 0.48	0.18 - 0.27	0.13 - 0.27
n = 6	80.28 - 94.35	320.18 - 394.4	8.03 - 9.43	29.94 - 44.04	0.61 - 0.75	0.37 - 0.40	0.15 - 0.23	0.13 - 0.25

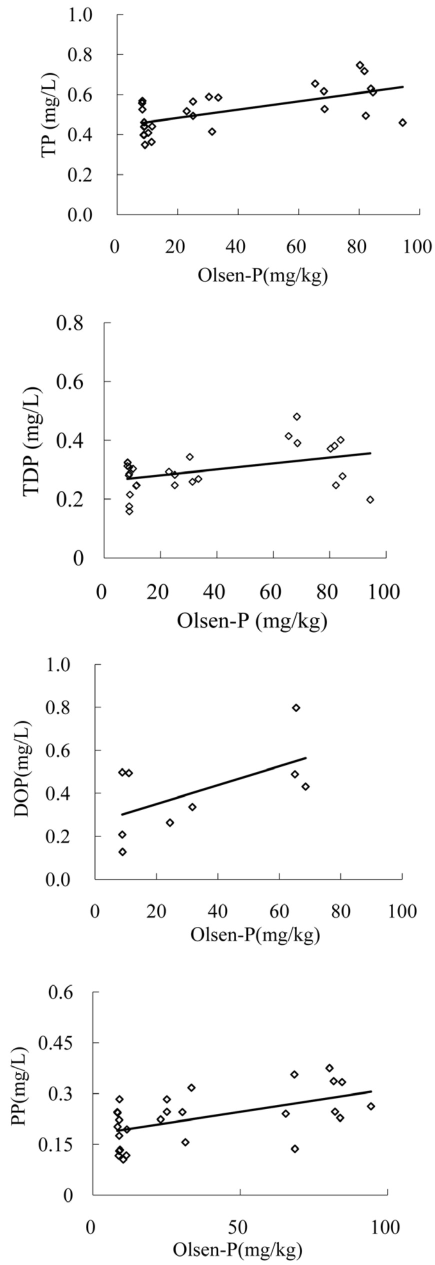

Figure 4. Correlation between the P concentrations of the four tests and Olsen-P (significant correlation on the 0.01 level).

of >40 and <70.90 mg/kg and PSI of >40 slightly influenced the environment. Olsen-P of >70.90 mg/kg and PSI of <30 had a significant influence on the eutrophication in Dianchi Lake Basin water environment. Meanwhile, greenhouse and some open fields with cultivated vegetables were considered key control objects.

3.4. Analysis on "Mutational Sites" Olsen-P in Soil and TP in Leachate

The correlation between Olsen-P and TP in the leachate was analyzed (**Figure 6**)

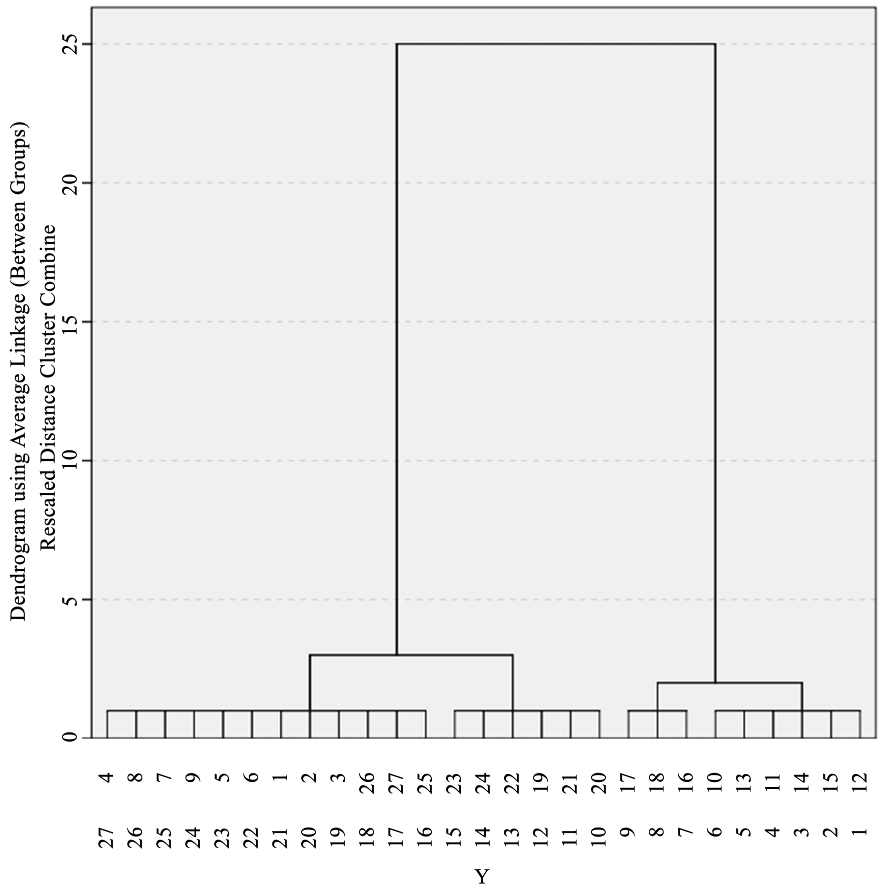

Figure 5. Clustering analysis on the different forms of P concentrations and soil layer data in the four tests.

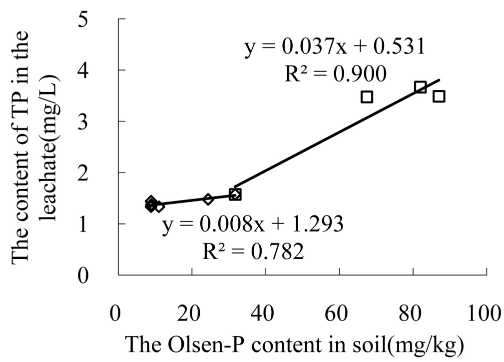

Figure 6. Correlation analysis between the TP in the leachates and Olsen-P.

to determine the "mutational sites" of Olsen-P in red soil and TP in leachates according to the above thresholds. The analysis yielded two duality formulas. When the Y values of the two duality formulas were similar, and Olsen-P was approximately 26.09 mg/kg, the first "mutational site" was obtained, indicating that the TP filtrates from the leachate in the water environment increased sharply when Olsen-P was >26.09 mg/kg. Therefore, Olsen-P was maintained at 26.09 mg/kg for the P requirements.

4. Discussions

Many outstanding research achievements in the world have been gained. For example, basing on the relationship between the Olsen-P in soil and MRP content in leachate, (Heckrath, 1995) identified the "mutational site" of P leaching in soi; (Lv, 2003) confirmed this mutational site. In the present experiment, the correlation curve between Olsen-P and CaCl2-P contents was formulated using Olsen-P content in soil as x-axis and TP content in the leachate as y-axis. Our findings indicate that Olsen-P of >70.90 mg/kg can cause water eutrophication. This result is consistent with Lv and Hesketh.

In this experiment, an obvious "mutational site" was discovered from the correlation curve between Olsen-P in soil and TP in leachate. When Olsen-P content in soil is maintained at 26.09 mg/kg, the soil P release can be controlled effectively. When Olsen-P was >26.09 mg/kg, the amount of P released from the soil to the environment increased sharply. This outcome is different from the research result of (Liu et al., 2019), who reported that soil with long-term application of P fertilizers reaches saturation when Olsen-P is <23 mg/kg. The reason is that their differences follow the order of the different soil types, land use patterns, and long-term applications of fertilizers.

5. Conclusions

1) The Olsen-P content in the red soil of Dianchi Lake Basin is divided into three levels according to land use pattern: Low level = 9 mg/kg (grassland), middle level = 30 mg/kg (open vegetable field), and high level = 90 mg/kg (greenhouse). The NaOH-P and $CaCl_2$-P contents in red soil are consistent with Olsen-P content. Their trends follow the order of greenhouse > open field > grassland. Meanwhile, the PSI trend follows the order of grassland > greenhouse > open field.

2) At the same land use pattern, PP > TDP > DOP > MRP, as indicated by the soil pillar simulation test results. The average TP contents in the leachates of grassland, greenhouse, and open field are 0.46, 0.61, and 0.49 mg/L, respectively. The TDP and TP contents and distributions of the three land-use patterns are similar. Meanwhile, the MRP contents in the leachates of grassland and open field are both 0.14 mg/L, which is slightly lower than that in the greenhouse. The greenhouse has the highest PP, followed by the open field and grassland successively. The maximum DOP content (0.27 mg/L) is obtained in the leachate of the greenhouse. The average DOP content in the grassland and open field is 0.13 mg/L, and the lowest DOP content is obtained in the grassland (0.076 mg/L).

3) Olsen-P is significantly correlated with TP, TDP, PP, and DOP, as indicated by the results of the correlation analysis between Olsen-P and different forms of P in the leachates. According to the results of the clustering analysis and presenc of available TP in the lake, Olsen-P of <40 mg/kg and PSI of >50 slightly influence water eutrophication in red soil of Dianchi Lake Basin. Moreover, Olsen-P of >40 and <70.90 mg/kg and PSI of >40 have a minimal effect on the environ-

ment. Olsen-P of >70.90 mg/kg and PSI of <30 can intensify water eutrophication in the Dianchi Lake Basin.

4) The correlation curve between Olsen-P and TP is obtained from the leachate data collected from the soil pillar simulation test. The TP content in the leachate increases sharply when Olsen-P is >26.09 mg/kg. Therefore, maintaining Olsen-P within 26.09 mg/kg during agricultural production is necessary.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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