Effect of Hydrothermal Coupling on Phosphorus Bioavailability in Vegetable Soil

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Abstract In this paper, the vegetable field in the teaching base of College of Agriculture, Yangtze University was taken as the research object. The indoor simulation method was used to explore the effects of temperature and moisture on the phosphorus (P) bioavailability of vegetable soil. Three temperature gradients [T1 (15 ℃), T2 (25 ℃), T3 (35 ℃)] and three humidity gradients [W1 (40%), W2 (70%), W3 (100%)] were set in the test. The results showed that it could improve the contents of HCl-P, Enzyme-P, Citrate-P, and Olsen-P in vegetable soil by increasing soil moisture content; temperature rise was helpful to increase the contents of HCl-P and Olsen-P, but it could reduce the content of Citrate-P. The contents of Enzyme-P and $CaCl_2$-P were significantly affected by hydrothermal interaction. Within a certain range of soil temperature and humidity, temperature and moisture had a positive coupling effect on soil P bioavailability components, and significantly affected soil P supply capacity.

Key words Vegetable field; Hydrothermal coupling; Soil phosphorus; Phosphorus bioavailability; Interaction

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Phosphorus (P) is an essential nutrient element for plant growth and development, and plays a key role in plant physiological process[1], which is of great significance for improving crop yield and quality. The bioavailability of soil P not only affects crop growth, but also is a key factor in the balance of terrestrial ecosystem[1]. The use of P-fertilizer in China accounts for about 25% of the world's total, but 74% of arable land is facing the problem of P deficiency. Because 95% of the phosphorus in the soil is insoluble, the total P content is high, and the available P content (Olsen-P) is low, resulting in a general lack of P in terrestrial plants[2–3]. Water and temperature significantly affect the migration and transformation of soil available P[4]. The extreme drought and precipitation events triggered by global climate change exacerbated the soil drying – rewetting (DRW) cycle, and profoundly affected the geochemical P cycle. Precipitation changes are closely related to soil nutrients and plant photosynthetic physiology. Excessive precipitation could lead to soil P leaching. In order to ensure the yield of vegetables, a large amount of P-fertilizer could lead to poor growth of vegetables, quality decline, and water pollution. Soil P bioavailability in vegetable fields is closely related to water and temperature[5]. It is crucial to comprehensively evaluate and improve soil P availability by exploring the impact of both on soil P bioavailability. Cai Guan *et al.*[6] found that the available P in upland soil mainly came from $CaCl_2$-P and Enzyme-P, and the content of each P component in upland was significantly higher than that in paddy field by using the biologically-based phosphorus method (BBP method). Many studies have shown that temperature had an important impact on the migration, transformation and availability of available phosphorus[7–10]. Therefore, this paper used P classification method to carry out simulation research on the vegetable soil in Jianghan Plain. It aimed to provide reference for the rational application of P-fertilizer in southern vegetable fields, reducing fertilizer waste and agricultural non-point source pollution.

1 Materials and methods

1.1 Materials The vegetable field is located in the teaching base of College of Agriculture, Yangtze University, and belongs to the agricultural climate zone in the middle and lower reaches of the Yangtze River. The total annual solar radiation in Jingzhou City is 104 – 110 kcal/cm^2, the annual sunshine hours are 1 800 – 2 000 h, the average annual temperature is 16.5 ℃, and the average annual precipitation is about 1 150 mm. The groundwater level is about 4 m, and it is the main production area of grain, cotton and oil. The basic physical and chemical properties of the topsoil (0 – 20 cm) of the experimental field are as follows: total nitrogen 2.16 g/kg, alkali hydrolyzable nitrogen 124.52 mg/kg, total phosphorus 0.86 g/kg, total potassium 6.05 g/kg, available phosphorus 28.94 mg/kg, available potassium 54.93 mg/kg, and pH 7.6.

1.2 Experimental design This experiment took vegetable soil as the research object. Three temperature gradients (T1, T2, T3) and three humidity gradients (W1, W2, W3) were set. 200 g of uniform soil was taken and put into the petri dish. Then, they were placed in the constant-temperature incubator with set temperature and humidity for shading culture for 15 d. During this period, it should observe and replenish water in time every day. After 15 d, samples were taken to analyze the relevant indicators.

1.3 Methods

1.3.1 Soil sample collection. The soil from the farming layer of

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vegetable field (0 – 20 cm, planting cabbage for more than 8 a) was collected. After passing 2 mm of sieve, it was mixed evenly for standby, and the basic physical and chemical properties were determined.

1.3.2 Determination of soil P bioavailability by BBP method. The free diffusing or rhizosphere retained phosphorus ($CaCl_2$-P), organic acid activated and inorganic weakly bound phosphorus (Citrate-P), organic phosphorus mineralized by a series of enzymes (Enzyme-P), and potentially activated inorganic phosphorus pool (HCl-P) were determined. 10 ml of 0.01 mol/L $CaCl_2$, 10 ml of 0.02 EU (enzyme unit)/ml enzyme solution, 10 ml of 0.01 mol/L Citrate (citric acid) solution, and 10 ml of 1 mol/L HCl were added respectively to a centrifuge tube containing 0.5 g of fresh soil for parallel extraction. They were oscillated for 3 h at 180 r/min (25 ℃), and then 1 ml was sucked into a 1.5 ml of centrifuge tube for centrifugation for 1 min at 100 000 r/min (25 ℃). After that, the supernatant was extracted and put into the enzyme plate. The contents of $CaCl_2$-P, Citrate-P, Enzyme-P and HCl-P were determined by malachite green colorimetry at the wavelength of 630 nm using a multifunctional microplate reader. At the same time, the Olsen-P content in each treatment soil was measured by $NaHCO_3$ extraction.

1.4 Data processing The test data were processed and plotted by Microsoft Excel 2019 and SPSS, and the LSD method was used to test the significant difference at the $P<0.05$ level.

2 Results

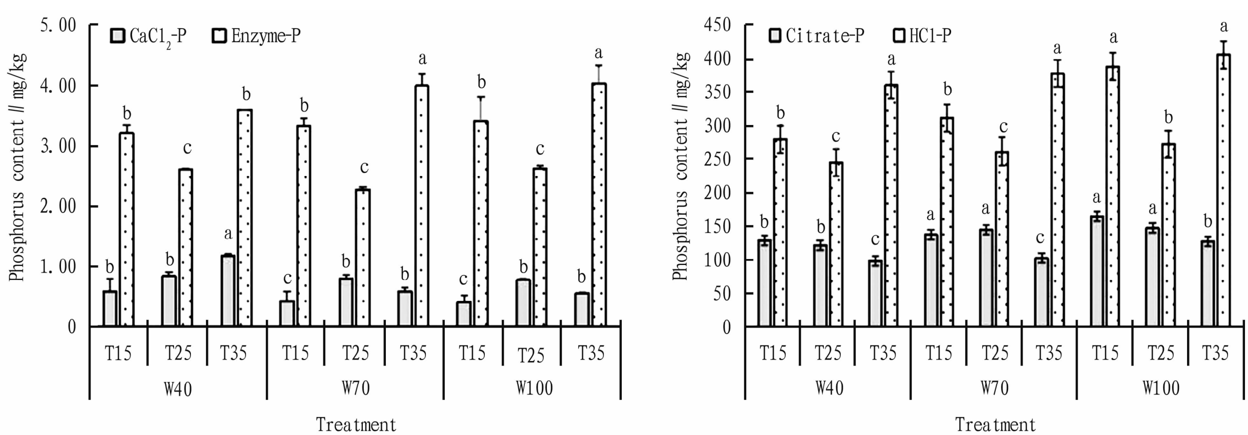
2.1 Variance analysis of P components in vegetable fields under moisture and temperature changes It can be seen from Table 1 that moisture and temperature had significant effects on the contents of Citrate-P, Enzyme-P and HCl-P in vegetable fields, and there were interactions. Temperature had extremely significant effects on the contents of Citrate-P, Enzyme-P and HCl-P in vegetable soil ($P<0.01$); moisture had significant effects on the contents of Citrate-P, Enzyme-P and HCl-P in vegetable soil ($P<0.05$); the interaction of moisture and temperature had a significant effect on soil enzyme phosphorus content in vegetable fields ($P<0.05$). The effects of moisture, temperature, and the interaction of moisture and temperature on $CaCl_2$-P were not significant.

Table 1 Variance analysis on effects of different moisture and temperature on P components in vegetable soil

Item		$CaCl_2$-P	Citrate-P	Enzyme-P	HCl-P
P value	T	0.067	0.000***	0.000***	0.000***
	W	0.110	0.000***	0.037*	0.018*
	T*W	0.493	0.549	0.046*	0.471
F value	T	2.867	15.879	136.136	19.979
	W	2.319	11.016	3.974	5.090
	T*W	0.863	0.779	3.006	0.926

Note: In the analysis of variance, *, ** and *** indicated that there were significant differences between treatments at the levels of $P=0.05$, $P=0.01$ and $P=0.001$, respectively.

2.2 Effects of hydrothermal coupling on P components in vegetable fields Fig. 1 showed the effects of different moisture and temperature on the contents of phosphorus bioavailable components in vegetable soil. The contents of soil phosphorus components from low to high were as follows: $CaCl_2$-P < Enzyme-P < Citrate-P < HCl-P, and their average contents were 322.5, 130.2, 3.2 and 0.7 mg/kg, respectively. Among them, Citrate-P content decreased with temperature, and the largest decrease amplitude was 22.9%; the variation of Enzyme-P content with temperature was not obvious; The content of $CaCl_2$-P was not significantly affected by temperature and moisture. Under the same moisture condition, the content of HCl-P first decreased and then increased with temperature, especially at 25 ℃, it temporarily decreased due to other factors, indicating that both moisture and temperature had an effect on the content of HCl-P. In addition, the contents of Citrate-P and Enzyme-P rose with the increase of moisture content at the same temperature, with the maximum increase of 28.1% and 12.2% respectively, reflecting the significant effect of moisture on the two phosphorus components.



Note: The data with different lowercase letters in each P component were significantly different ($P=0.05$).

Fig. 1 Effects of different moisture and temperature on the contents of P components in vegetable soil

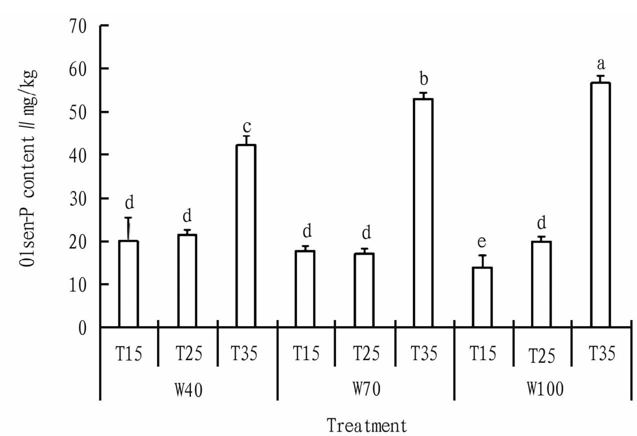
2.3 Variance analysis of soil Olsen-P under different moisture and temperature conditions Table 2 showed that temperature had an extremely significant effect on Olsen-P content in vegetable fields ($P<0.001$), while moisture and hydrothermal interaction had no significant effect. It can be seen that temperature was more dominant than moisture in affecting Olsen-P. Temperature can affect the process of chemical reaction, enzyme activity, and soil microbial activity; moisture mainly affects microbial activity as a biological cell solvent. In this experiment, because the moisture content was not extreme, 100% moisture content had the most prominent effect on soil gas permeability, which was worthy of attention.

Table 2 Variance analysis of Olsen-P content in vegetable soil under different moisture and temperature conditions

P value			*F* value		
T	W	T * W	T	W	T * W
0***	0.879	0.395	36.111	0.131	1.146

Note: In the analysis of variance, *, ** and *** indicated that there were significant differences between treatments at the levels of $P=0.05$, $P=0.01$ and $P=0.001$, respectively.

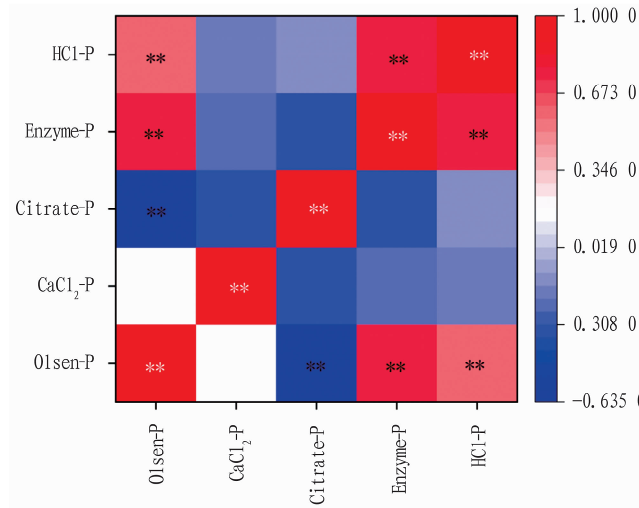
2.4 Effect of hydrothermal coupling on the content of Olsen-P in vegetable soil It can be seen from Fig. 2 that the Olsen-P content of vegetable soil increased as the temperature rise when the moisture content remained unchanged, with an increase amplitude of 111.4% to 311.6%. Under the same temperature condition, it first decreased and then increased with the increase of moisture content. The content of Olsen-P reached the highest value of 56.51 mg/kg at 35 ℃ and 100% moisture gradient. It was speculated that there was hydrothermal interaction at 25 ℃, and the related mechanism needed to be studied.



Note: The data with different lowercase letters in each phosphorus component were significantly different ($P=0.05$).

Fig. 2 Effects of different moisture and temperature on Olsen-P content in vegetable soil

2.5 Correlation between P available components and Olsen-P in vegetable soil As shown in Fig. 3, the correlation between available phosphorus (Olsen-P) and soil P bioavailability was shown in the heat map. The color could directly reflect the correlation, and the color depth could show the strength. In vegetable field, Olsen-P content was significantly positively correlated with Enzyme-P content ($R^2=0.5315$, $P<0.01$) and HCl-P content ($R^2=0.327$, $P<0.01$), and significantly negatively correlated with Citrate-P content ($R^2=0.4026$, $P<0.01$), but not significantly correlated with $CaCl_2$-P content ($R^2=0.0232$, $P<0.05$).



Note: ** and * showed significant correlation at the levels of 0.01 and 0.05 (bilateral), respectively. The correlation coefficients of 0.8−1.0, 0.6−0.8, 0.4−0.6, 0.2−0.4 and 0−0.2 indicated extremely strong correlation, strong correlation, moderate correlation, weak correlation, extremely weak correlation or no correlation, respectively; negative values were negatively correlated.

Fig. 3 Correlation between P content and Olsen-P content in soil

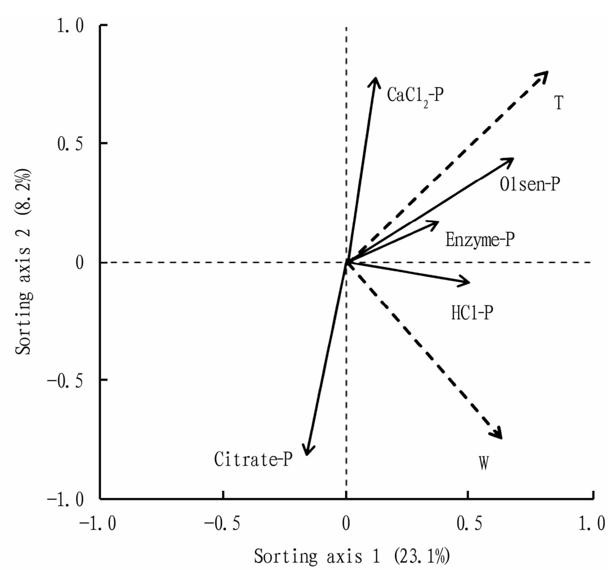


Fig. 4 Redundancy analysis of P components with moisture and temperature in vegetable soil

2.6 Redundancy analysis of P components with moisture and temperature in vegetable soil The redundancy analysis on the effects of moisture and temperature on the bioavailable phosphorus components of vegetable soil showed that moisture had the greatest effect on Citrate-P, followed by HCl-P, Enzyme-P, and Olsen-P. Temperature had the greatest effect on Olsen-P and $CaCl_2$-P, followed by Enzyme-P and HCl-P. From the sorting axis, it can be clearly seen that temperature and moisture had respective effects on available phosphorus and soil bioavailable phosphorus components, which were important factors for soil phosphorus transformation (Fig. 4).

3 Discussion

In recent years, a lot of researches on soil phosphorus have been carried out. Li Shuaishuai *et al.* [11] pointed out that there was a significantly positive correlation between the active phosphorus pool and the soil available phosphorus content. Using drip irrigation, it was also found that reasonable control of soil moisture could significantly increase the contents of soil nitrogen, phosphorus and potassium. In this paper, different moisture and temperature conditions were set for vegetable soil. The results showed that (Table 1) the contents of Enzyme-P, Citrate-P and HCl-P increased significantly with the increase of moisture content when the soil temperature was constant; the moisture content of flooding treatment (100%) had the most significant effect on the five test indexes. This was because soil flooding reduced soil permeability, affecting nitrification, and organic acids increased phosphorus solubility, which was consistent with the study of Erinle *et al*[12]. The moisture gradient had a significant effect on the contents of Citrate-P and HCl-P in vegetable soil, but had no significant effect on the content of $CaCl_2$-P. It was because that the sampling area was located in Jianghan Plain in the middle reaches of the Yangtze River, and the soil weathering leaching intensity was high, which made the soil more iron phosphorus and less calcium phosphorus, and the content of $CaCl_2$-P was low. In the moisture treatment (Fig. 2), the content of Olsen-P in the soil of 100% moisture treatment (W100) was the highest, which was in line with previous studies[13]. This was because Fe^{3+} was reduced to Fe^{2+} in the flooded reducing state, releasing available phosphorus[14-15].

Temperature is also a key factor affecting soil phosphorus. In this paper (Fig. 1 and Fig. 2), the contents of HCl-P, Enzyme-P and Olsen-P in vegetable soil reached the peak at 35 ℃. Redundancy analysis (Fig. 4) showed that temperature contributed 49.0% to the impact of bioavailable phosphorus components. Warming can increase the activity of soil available nutrients, The research of Wang Liangli *et al.* [16] has shown that the content of Olsen-P in soil increased with the temperature rise, which was consistent with this paper. The temperature rise promoted the decomposition of soil minerals and mineralization of organic matter, strengthened microbial respiration, and was conducive to phosphorus activation. It was also found that the content of available phosphorus in vegetable fields was positively correlated with cultivation years[17-18]. The interaction of moisture and temperature (Fig. 1) showed that the hydrothermal coupling had a significant effect on the contents of $CaCl_2$-P and Enzyme-P in vegetable soil, but had no obvious effect on other phosphorus components. Soil moisture participated in most soil reactions and affected the transformation of phosphorus by microorganisms[19-22]. Soil temperature affected microbial activity, and low temperature reduced phosphorus availability[23].

The purpose of this paper was to improve the understanding of the interaction between soil moisture and temperature and the availability of phosphorus in vegetable soil. Single moisture or temperature factor had an extremely significant effect on the components of bioavailable phosphorus in vegetable soil, but the hydrothermal coupling effect was not significant, which needed to be further studied. In addition, the BBP phosphorus classification method was used in this experiment. Part of the organic phosphorus was encapsulated, although it can be released and detected by reagent, it cannot be mineralized by microorganisms under natural conditions, which could lead to deviation in the bioavailability evaluation of organic phosphorus. Moreover, the impact of differences in vegetable planting and fertilization on the microorganisms are complicated. In the future, the content of organic phosphorus released by microbial mineralization can be compared.

4 Conclusions

In vegetable soil, the contents of P components showed the relationship of $CaCl_2$-P < Enzyme-P < Citrate-P < HCl-P. When the temperature remained stable, the contents of HCl-P, Citrate-P, Enzyme-P and Olsen-P increased with the increase of soil moisture. In the temperature range from 10 to 40 ℃, the soil temperature rise could increase the contents of HCl-P and Olsen-P, and reduce the content of Citrate-P. The hydrothermal coupling was significantly correlated with the contents of $CaCl_2$-P and Enzyme-P in vegetable soil. In addition, the content of Olsen-P was positively correlated with the contents of HCl-P and Enzyme-P, but negatively correlated with the contents of Citrate-P and $CaCl_2$-P. These conclusions clearly revealed the influence of moisture, temperature and hydrothermal coupling on P in vegetable soil, and provided a key basis for scientific management of soil phosphorus, improvement of soil fertility and promotion of crop growth.

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protection education, ecological culture publicity and rural civilization construction have significant and positive effects on farmers' satisfaction with ecological governance, which shows that the development of environmental protection related education and the strengthening of ecological culture publicity by government departments can gradually improve farmers' ecological awareness and ecological protection ability. At the same time, strengthening the construction of rural ecological civilization can further improve the quality of the ecological environment in rural areas, strengthen the publicity and implementation of environmental protection laws and regulations, and ensure that rural residents have a profound understanding of the concept of ecological civilization.

According to the conclusion, it can strengthen the policy measures from the following aspects. First, it could strengthen the construction of legal system and consolidate the laws and regulations of ecological governance. Second, it could increase government investment in the environment, and ensure farmers' ecological governance capacity. Third, it should improve the ecological culture literacy and enhance farmers' awareness of ecological governance. Fourth, it should continue to improve the security of rural ecological environment and improve farmers' satisfaction with the ecological environment. The research aims to provide enlightenment and reference for the improvement of rural ecological governance ability in China, promote ecological sustainable development, and impel the implementation of rural revitalization strategy.

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