



# Improvement of P Use Efficiency and P Balance of Rice–Wheat Rotation System According to the Long-Term Field Experiments in the Taihu Lake Basin

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Phosphorus (P) accumulation in rice–wheat rotation fields around the Yangtze River delta have been enriched during the last decades. To protect the environment and save P resources, we conducted field experiments to optimize the P application scheme. First, one field experiment was designed as a series of P fertilizer application doses of 0–100 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup>. Grain yield and P uptake by crops were analyzed to calculate P surplus and P use efficiency. Soil P fractions were extracted and tested. According to the P balance, we optimized fertilization by reducing the chemical P amount, which was used by local farmers; furthermore, we substituted chemical P with organic fertilizer. To verify these management strategies, another field experiment was conducted with five treatments: no N, P, or K fertilizer (CK); only no P fertilizer (NK); farmers' fertilization of P (90 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup>) (FFP); reducing 20% P (FFP-20%P); and reducing 20% P and replacing 20% P by manure (FFPM-36%P). The grain yield was enhanced by increased P fertilizer and reached a constant level after 75 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup>. Moreover, the annual P surplus was balanced around the input of 150 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup>. Accordingly, by optimizing fertilization (FFP-20%P) and further replacing manure (FFPM-36%P), we also achieved crop yield equivalent to that of FFP treatment (90 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup>). Thus, the 72–75 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup> application rate is a threshold for the production of rice and wheat and P balance. Total P content in soil was enhanced by increased input of P fertilizer and mainly divided into labile Pi and middle stable Pi fractions. Soil Olsen-P content increased by P fertilization accordingly, while the content of organic P and stable P content was relatively constant. Reducing P fertilizer by 20% had similar results for soil P fractions when compared with farmers' P fertilization treatment. Therefore, reducing at least 20% current input of P by farmers (annual 180 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup>) according to the balance of P surplus in rice and wheat rotation systems is an imperative measure to guarantee crop production with enhanced P use efficiency, and meanwhile, it can alleviate environmental risk.

**Keywords:** rice–wheat rotation, P fertilizer, P surplus, P use efficiency, soil P fractions

## INTRODUCTION

Food security is always an important issue in Asia, where there is a large population (Thangavel and Sridevi, 2017). In China, the rice–wheat rotation system is one of the traditional agricultural practices along the Yangtze River Basin, with a planting area of 4.8 million hectares (Zhang et al., 2017), which provides important staple foods for people. In 2018, China's total rice and wheat production accounted for 27% and 18% of the global production, respectively (Muthayya et al., 2015). These huge crop productions in China were strongly dependent on the large inputs of chemical fertilizers, especially N and P (Qiu, 2009; Qiu, 2010; Cui et al., 2018). According to the data from the National Bureau of Statistics (<https://www.ceicdata.com/zh-hans/china/consumption-of-chemical-fertilizer-phosphate>), P fertilizer applied in 2019 amounts to 6.815 million tons. The annual application amount of P fertilizer from 1979 to 2019 is an average of 6.890 million tons. The value peaked in 2014, at about 8.453 million tons from the lowest value in 1979, about 2.235 million tons. The heavy fertilizer use has made China one of the biggest fertilizer consumers in the world. Therefore, such an agricultural mode had adverse negative effects on the environment, such as the increase in greenhouse gas emissions (Chen et al., 2014; Cui et al., 2018), soil acidification (Guo et al., 2010), eutrophication (Le et al., 2010), and biodiversity loss in soil

(Clark and Tilman, 2008). The Yangtze River Basin is an important agricultural area in China due to enough water and temperature resources for paddy rice cultivation. However, the Yangtze River Basin has consistently accumulated phosphorus since 1980 due to intensive agriculture with high input of P (Powers et al., 2016).

Thus, it is urgent to re-evaluate the input of fertilizers, seasonal crop production, accumulation, and balance of nutrient elements in the local agricultural system. Phosphorus (P) is one of the important fertilizers for crop growth and yield. However, P is easily absorbed by oxides of Al or Fe or precipitated by Ca in the soil, which leads to low P use efficiency (Holford, 1997). To achieve high crop production, farmers apply the P fertilizer every season in high amounts, due to the lack of information regarding the present values of available P in soil. In the Yangtze River delta near the Taihu Lake, average yields of rice and wheat in the area were reported to be around 7,500 and 4,500 kg hm<sup>-2</sup> during the wet and dry rotation, respectively (Zhao et al., 2009). However, due to the high rate of chemical P fertilizer application, the phosphorus content in farmland soil in Taihu Lake Basin has been increasing over the last 40 years. The Olsen-P concentration in 65% of soil samples in this region was over 20 mg kg<sup>-1</sup> soil (Wang S. Q. et al., 2012; Wang et al., 2022); in contrast, it was only several mg kg<sup>-1</sup> in the 1980s. Since the environmental threshold of soil Olsen-P in the local fields is about 30 mg kg<sup>-1</sup>, the overapplication of chemical P fertilizer or

**TABLE 1** | Fertilizers for wheat and rice cultivation (kg·hm<sup>-2</sup>).

Treatment	Base fertilizer			Tillering fertilizer		Panicle fertilizer	
	N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O (wheat/rice)	N	N	K <sub>2</sub> O (wheat/rice)	
P <sub>0</sub>	120	0	45/90	90	90	45/0	
P <sub>25</sub>	120	25	45/90	90	90	45/0	
P <sub>50</sub>	120	50	45/90	90	90	45/0	
P <sub>75</sub>	120	75	45/90	90	90	45/0	
P <sub>100</sub>	120	100	45/90	90	90	45/0	
CK	0	0	0	0	0	0	
NK	120	0	45/90	90	90	45/0	
FFP	120	90	45/90	90	90	45/0	
FFP-20%P	120	72	45/90	90	90	45/0	
FFPM-36%P	120	57.6	45/90	90	90	45/0	

**TABLE 2** | Effect of P fertilization rates on rice yield.

Treatment	Straw yield (kg·hm <sup>-2</sup> )	Grain yield (kg·hm <sup>-2</sup> )	Increased (%)	Harvest index(%)
2016 rice				
P <sub>0</sub>	13208c	7519d	-	56.9b
P <sub>25</sub>	14905ab	8585c	14	57.5a
P <sub>50</sub>	15690ab	9089a	20	57.9a
P <sub>75</sub>	16080a	9325a	24	57.9a
P <sub>100</sub>	15958b	9145b	21	57.3a
2017 rice				
P <sub>0</sub>	13593c	8208b	-	60.3a
P <sub>25</sub>	15424ab	8806b	7	57.1b
P <sub>50</sub>	15455ab	9210a	12	59.6a
P <sub>75</sub>	15799a	9390a	15	59.4a
P <sub>100</sub>	15544b	9180b	12	59.1a

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

**TABLE 3** | Effect of P fertilization rates on wheat yield.

Treatment	Straw yield (kg·hm <sup>-2</sup> )	Grain yield (kg·hm <sup>-2</sup> )	Increased (%)	Harvest index (%)
2016–2017 wheat				
P <sub>0</sub>	9311c	3299c	-	35.4c
P <sub>25</sub>	10935b	4075b	13	37.2b
P <sub>50</sub>	12520ab	4708a	29	36.7b
P <sub>75</sub>	12709a	4898a	44	39.2a
P <sub>100</sub>	12911a	4947a	38	38.1a
2017–2018 wheat				
P <sub>0</sub>	9487c	3345d	-	35.2b
P <sub>25</sub>	10753b	4277c	27	37.0ab
P <sub>50</sub>	11986a	4598b	37	38.2ab
P <sub>75</sub>	12825a	5047a	50	39.3a
P <sub>100</sub>	12589a	4854ab	45	38.0a

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

compound fertilizer brought a great risk to the environment (Powers et al., 2016), and further decreased P use efficiency and wasted P resources (Alewell et al., 2020).

In the present study, we conducted a field experiment with a series of P fertilization rates to check the effect of P input on the crop yield and P surplus in the current rice and wheat rotation system. Furthermore, we reduced the current farmers' application dose of P fertilizer and combined it with organic manure to get an optimized regime of P fertilization in the Taihu Lake delta. Our aim is to find a practical and feasible fertilization strategy to guarantee crop production and reduce risk to the environment for sustainable agriculture.

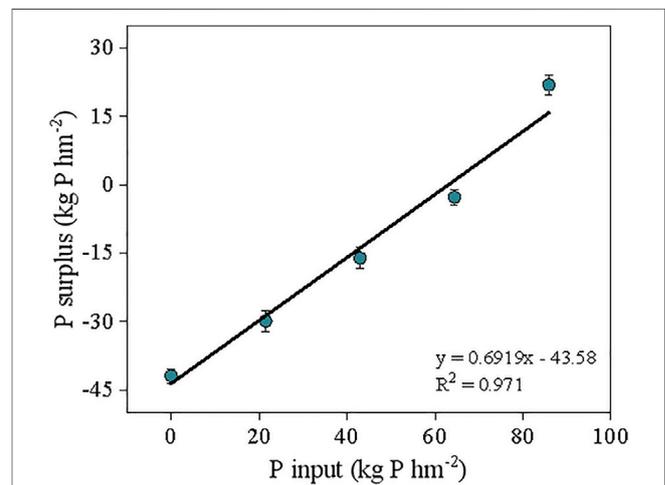
## MATERIALS AND METHODS

### Field Experiments Description

Field trials were conducted on a farm in Yixing City, in the Yangtze River delta in the northeast of China (31°41'N, 120°40'E). This region has a subtropical semi-humid monsoon climate, with an average annual temperature of 15.2°C and annual rainfall of 1,286 mm. About 50% of the precipitation is distributed from April to June. The soil was paddy soil, consisting of 12% sand, 45% silt, and 43% clay. The initial soil pH was 6.21 (1:1, water/soil, w/w). In the surface soil (0–20 cm), the total nitrogen is 13.6 g kg<sup>-1</sup>, the organic carbon is 12.8 g kg<sup>-1</sup>, the available P is 22.8 mg kg<sup>-1</sup>, and the available K is 64.9 mg kg<sup>-1</sup>.

The field trials were divided into two parts. First, the different P fertilization amounts were applied beginning in 2016. There are five treatments: P<sub>0</sub>, P<sub>25</sub>, P<sub>50</sub>, P<sub>75</sub>, and P<sub>100</sub> (representing 0–100 kg P<sub>2</sub>O<sub>5</sub> hm<sup>-2</sup> of P fertilizer, respectively). The plot size was 7 × 5 = 35 m<sup>2</sup> with a 50-cm wide walkway between the plots. Another field experiment had five treatments, including control (CK), no phosphate fertilizer (NK), conventional fertilization by farmers (FFP), FFP reduced P by 20% (FFP-20%P), and organic substitution plus or minus P by 36% (FFPM-36%P). The plot size was 8 × 10 = 80 m<sup>2</sup> with a 50-cm wide walkway between the plots. All treatments had four repetitions, and plots are randomly arranged in the fields.

The local cultivar of rice and wheat were Nangeng 46 and Yangmai 5, respectively. In the rice season, rice seedlings were prepared and



**FIGURE 1** | The relationship between the annual P input and the P surplus in rice and wheat rotation according to two years under a series of P fertilization amount treatment.

transplanted at 30,000 holes per hectare, while wheat was directly planted at 50,000 plants per hectare. Urea was used as N fertilizer, and superphosphate and potassium chloride were used as P and K fertilizers. The organic fertilizer was manufactured by a local factory with organic matter of 40% and total N, P, and K of 6%. Urea was applied as basal fertilizer and two top dressings with a ratio of 4:3:3 (Table 1). P, K, and organic fertilizers were applied as basal fertilizers.

### Crop Yield Estimation

Crops were manually harvested with all the above-ground parts from each plot. The grain and straw were separated by a threshing machine. Yield components and P concentration of grain and straw were analyzed.

### Soil P Analysis

Soil samples (0–20 cm depth) from each plot were collected after crop harvest, air-dried, ground, sieved (< 2 mm sieve), and stored

**TABLE 4 |** Effect of P fertilization rates on P uptake and P surplus.

Treatment	Wheat		Rice		Anniversary	
	P uptake (kg P-hm <sup>-2</sup> )	P surplus (kg-hm <sup>-2</sup> )	P uptake (kg P-hm <sup>-2</sup> )	P surplus (kg P-hm <sup>-2</sup> )	P uptake (kg P-hm <sup>-2</sup> )	P surplus (kg P-hm <sup>-2</sup> kg-hm <sup>-2</sup> )
Year 2016–2017						
P <sub>0</sub>	16.9c	-16.9	26.9d	-26.9	43.8c	-43.8
P <sub>25</sub>	18.4bc	-7.5	31.3c	-20.4	49.8c	-28.0
P <sub>50</sub>	22.5ab	-0.7	36.2b	-14.3	58.7b	-15.0
P <sub>75</sub>	26.6a	6.1	40.8a	-8.0	67.4a	-1.9
P <sub>100</sub>	23.6ab	20.0	43.6a	0.1	67.2a	19.9
Year 2017–2018						
P <sub>0</sub>	16.2d	-16.2	26.1d	-26.1	42.4c	-42.4
P <sub>25</sub>	19.5c	-8.6	30.1c	-19.1	49.6bc	-27.8
P <sub>50</sub>	22.3b	-0.4	35.0b	-13.2	57.3b	-13.6
P <sub>75</sub>	25.1a	7.6	41.2a	-8.4	66.3a	-0.8
P <sub>100</sub>	24.4a	19.2	42.3a	1.3	66.7a	20.6

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

**TABLE 5 |** Effect of optimized fertilization on rice yield.

Treatments	Straw yield (kg-hm <sup>-2</sup> )	Grain yield (kg-hm <sup>-2</sup> )	Increased (%)	Harvest index (%)
2018 rice				
CK	11550c	6480c	-	56b
NK	13692b	8391b	29.4	57a
FFP	15647a	8983a	38.6	57a
FFP-20%P	15790a	9190a	41.8	58a
FFPM-36%P	15960a	9219a	42.2	57a
2019 rice				
CK	11932c	6172c	-	51b
NK	13769b	8410b	36.2	61a
FFP	15772a	9012a	46.0	57a
FFP-20%P	16187a	9135a	48.0	56a
FFPM-36%P	16356a	9245a	49.8	56a

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

**TABLE 6 |** Effect of optimized fertilization on wheat yield.

Treatments	Straw yield (kg-hm <sup>-2</sup> )	Grain yield (kg-hm <sup>-2</sup> )	Increased (%)	Harvest index(%)
2018–2019 wheat				
CK	8045c	2915c	-	36b
NK	9368b	3669b	25.84	39a
FFP	12885a	4939a	69.43	38ab
FFP-20%P	13087a	4881a	67.44	37ab
FFPM-36%P	13290a	4994a	71.3	37ab
2019–2020 wheat				
CK	7682c	2674d	-	34b
NK	8679b	3782c	41.45	43a
FFP	12702a	4872b	82.23	38ab
FFP-20%P	12914a	4992a	86.72	38ab
FFPM-36%P	13309a	5022a	87.83	37ab

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

**TABLE 7** | Effect of optimized fertilization on P uptake and P surplus.

Treatment	Wheat		Rice		Anniversary	
	P uptake (kg P·hm <sup>-2</sup> )	P surplus (kg·hm <sup>-2</sup> )	P uptake (kg P·hm <sup>-2</sup> )	P surplus (kg P·hm <sup>-2</sup> )	P uptake (kg P·hm <sup>-2</sup> )	P surplus (kg P·hm <sup>-2</sup> )
2018–2019 year						
CK	10.5c	-10.5	18.8b	-18.8	29.4c	-29.4
NK	16.0b	-16.0	25.6ab	-25.6	41.6b	-41.6
FFP	23.9a	15.3	34.4a	4.9	58.3a	20.3
FFP-20%P	26.5a	4.96	36.5a	-5.1	63.0a	-0.1
FFPM-36%P	27.1a	4.36	34.3a	-2.9	61.4a	1.4
2019–2020 year						
CK	10.1c	-10.1	18.0b	-18.0	28.1c	-28.1
NK	15.6b	-15.6	24.3ab	-24.3	40.0b	-40.0
FFP	24.7a	14.5	35.9a	3.3	60.7a	17.9
FFP-20%P	26.4a	5.0	38.9a	-7.4	65.3a	-2.3
FFPM-36%P	27.5a	3.9	36.0a	-4.5	63.6a	-0.6

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

**TABLE 8** | Effect of P fertilization rates on P use efficiency.

Treatment	Rice		Wheat	
	AE <sub>P</sub> (kg·kg <sup>-1</sup> )	RE <sub>P</sub> (%)	AE <sub>P</sub> (kg·kg <sup>-1</sup> )	RE <sub>P</sub> (%)
2016–2017 year				
P <sub>25</sub>	42.6a	17.8a	31.0a	6.1b
P <sub>50</sub>	31.4b	18.6a	28.2a	11.3a
P <sub>75</sub>	24.1b	18.6a	21.3b	12.9a
P <sub>100</sub>	16.3 c	16.7a	16.5c	6.7b
2017–2018 year				
P <sub>25</sub>	46.5 a	15.8a	37.3a	13.2a
P <sub>50</sub>	30.1b	17.7a	25.1b	12.2a
P <sub>75</sub>	22.7c	20.1a	22.7b	11.9a
P <sub>100</sub>	17.7d	16.1a	15.1c	8.2b

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

at room temperature for chemical analysis. Available P in soil was extracted with 0.5 M NaHCO<sub>3</sub> (pH 8.5) and determined using the molybdenum blue method (Olsen et al., 1954).

Various P fractions were sequentially extracted from soils by deionized H<sub>2</sub>O and anion exchange resin, 0.5 M NaHCO<sub>3</sub>, 0.1 M NaOH, and 1M HCl according to Tiessen and Moir (1993). 0.5 g air-dried soil samples were dispersed in the aforementioned 20 ml solution step by step and shaken for 16 h on a rotary shaker. The soil and supernatant were then separated by centrifugation for 10 min at 10,000 × g at 4°C. The P concentration in the supernatant was determined by a spectrometer at 700 nm (UV 2500, Japan;) using the ascorbic acid molybdenum blue method (Murphy and Riley, 1962). After all the extraction steps, the soil residual was digested with H<sub>2</sub>SO<sub>4</sub> and H<sub>2</sub>O<sub>2</sub> at 360°C for P analysis. Moreover, NaHCO<sub>3</sub> and NaOH extracts were halved to measure the total P and inorganic P. The amount of organic P in the extract was calculated based on the difference between total P in digestion and inorganic P in the extracts.

**TABLE 9** | Effect of optimized fertilization on P use efficiency.

Treatment	Rice		Wheat	
	AE <sub>P</sub> (kg·kg <sup>-1</sup> )	RE <sub>P</sub> (%)	AE <sub>P</sub> (kg·kg <sup>-1</sup> )	RE <sub>P</sub> (%)
2018–2019 year				
FFP	27.8c	17.3b	22.2c	14.9c
FFP-20%P	37.6b	24.6a	30.9b	22.1b
FFPM-36%P	47.6a	26.9a	40.5a	28.7a
2019–2020 year				
FFP	31.6c	19.9b	24.4c	16.3c
FFP-20%P	41.2b	29.0a	32.2b	22.7b
FFPM-36%P	53.4a	31.3a	40.8a	30.3a

Note: Different lowercases indicate significant differences between the treatments of the same year at 5% level by Duncan test.

## P Use Efficiency Calculation

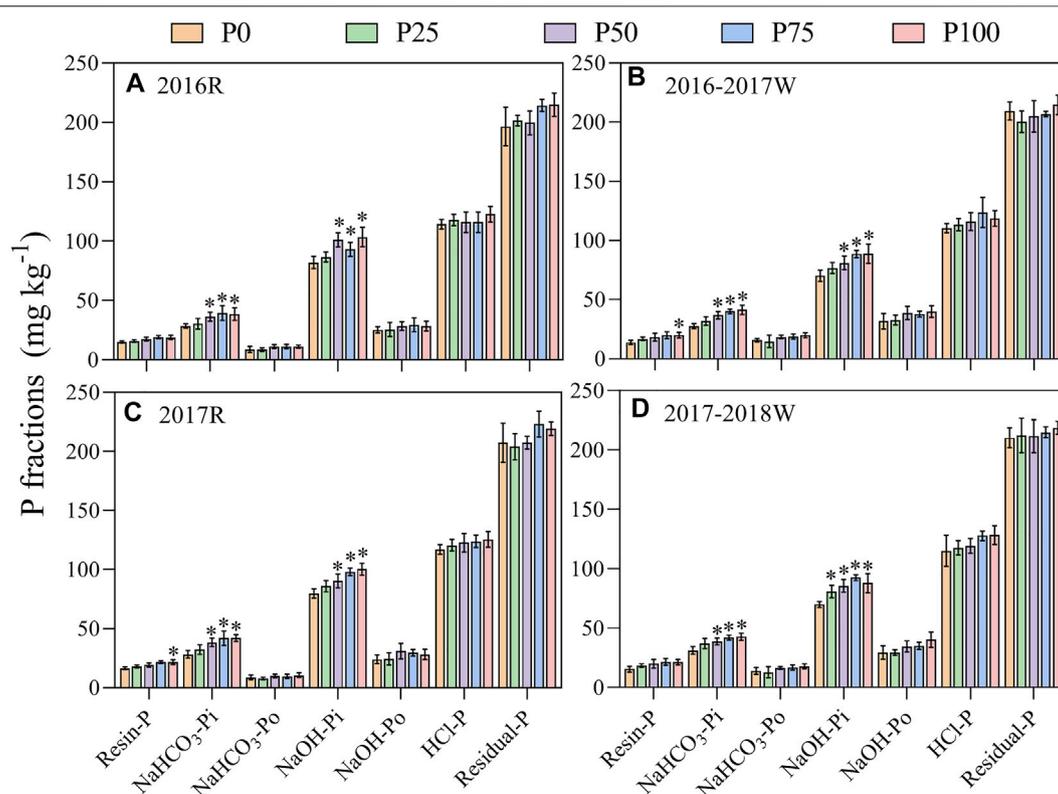
Agronomic efficiency of P:  $AE_P$  (kg·kg<sup>-1</sup>) = (yield under P fertilization – yield of blank)/P application dose; recovery efficiency of P:  $RE_P$  (%) = (P uptake by crop under P fertilization – P uptake by crop of blank)/P fertilization dose × 100%;

$$P \text{ uptake (kg·hm}^{-2}\text{)} = \text{biomass per unit area} \times P \text{ content};$$

$$P \text{ surplus (kg·hm}^{-2}\text{)} = (P \text{ application dose} - P \text{ accumulation}) \text{ per unit area.}$$

## Statistical Analysis

One-way analysis of variance (ANOVA) was conducted to explore the effects of different treatments on each variable (SPSS Statistics 19.0). Differences between treatments were tested using Duncan's test with the significance level set as alpha = 0.05. The structural equation modeling (SEM) was used to study the interaction and transformation of different P components (Hou et al., 2016) using IBM SPSS AMOS 22.0. Root mean square error of approximation (RMSEA) (<0.08), chi-



**FIGURE 2** | Variations in sequentially extracted P fractions under P fertilization rates on two-year rice-wheat rotation paddy field from 2016 to 2018.

square ( $\chi^2$ ) ( $\chi^2/df < 2$ ), and the  $p$  value of  $\chi^2$  ( $p > 0.05$ ) were used to evaluate the model fitting.

## RESULTS

### The Yield of Rice and Wheat Under Different P Fertilization Rates

Rice yield was enhanced by P fertilizer application rates from 0~100  $\text{P}_2\text{O}_5 \text{ hm}^{-2}$  (Table 2), including both grain and straw yield. However, the harvest index was not variable and ranged from 56~59%. The yield components of rice showed that the P fertilizer application rates significantly affected the panicle number and grain number per panicle, but not the thousand-grain weight and filled-grain percent (Supplementary Table S1). Combining the data from the two rice seasons, it was found the  $\text{P}_{75}$  treatment had the highest grain yield (Supplementary Figure S1A) with the highest panicle number and grain number per panicle (Supplementary Table S1) among all the treatments. Nevertheless, the yield of rice did not further increase with the treatment of  $\text{P}_{100}$ .

The wheat yield was also influenced by the application rates of P fertilizer (Table 3), with increased panicle number by elevated P input, while the grain number per panicle or thousand-grain weight was not changed (Supplementary Table S2). The grain yield of two wheat seasons under the  $\text{P}_{100}$  treatment was similar to that under  $\text{P}_{75}$  (Figure 1A).

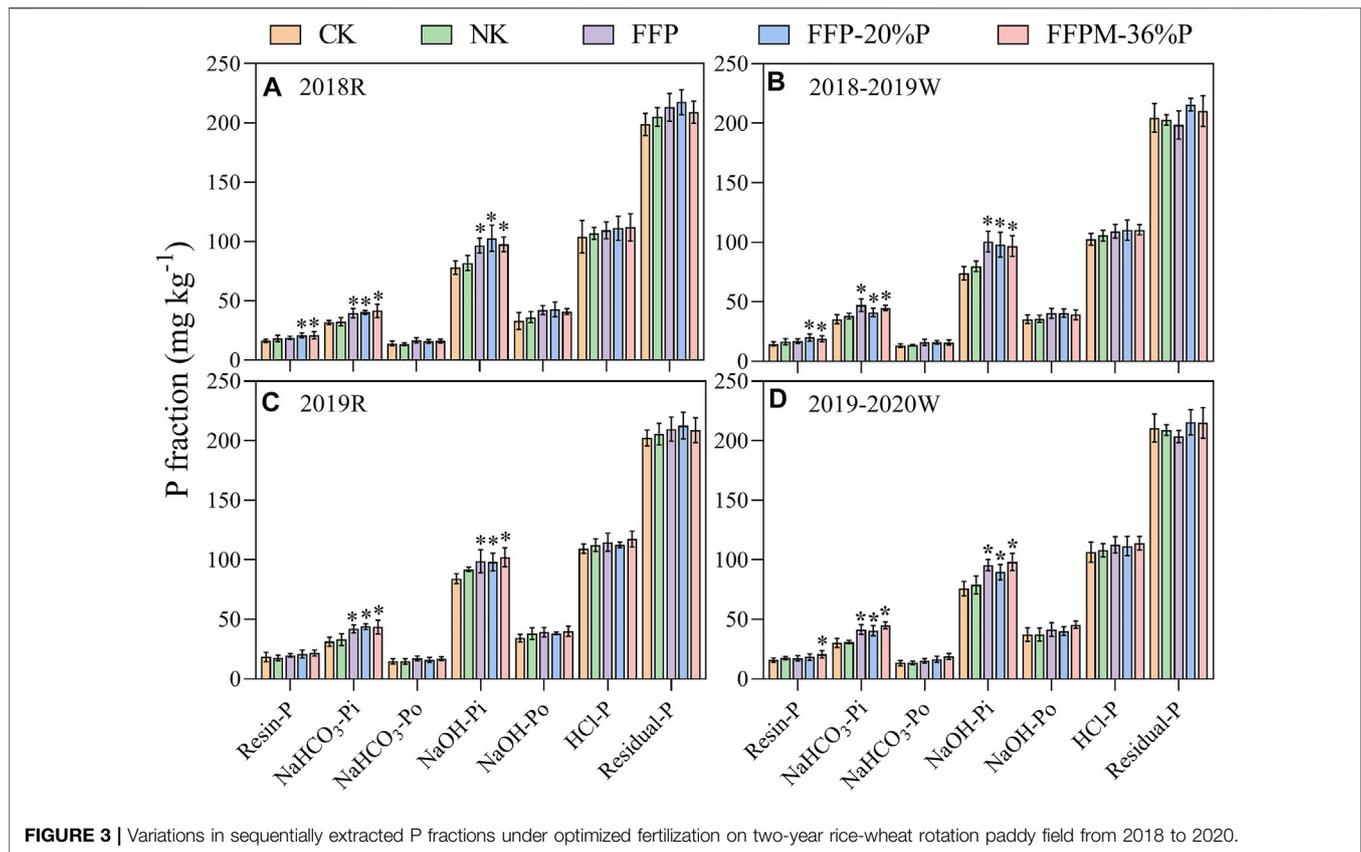
### P Uptake by Crops and P Surplus in Rice–Wheat Rotation System Under Different P Fertilization Rates

Since the total yield of aboveground biomass (straw and grain) of rice or wheat was related to the P application rates (Tables 2, 3), the total uptake of P, which accumulated in aboveground biomass of rice and wheat, also seemed dependent on the P application rates (Table 4). 75  $\text{kg P}_2\text{O}_5 \text{ hm}^{-2}$  input caused the highest P uptake by rice and wheat; however, additional input of P did not enhance P uptake as under  $\text{P}_{100}$  treatments. P surplus showed negative values before P input around 75  $\text{kg P}_2\text{O}_5 \text{ hm}^{-2}$  and became positive after  $\text{P}_{75}$  treatment.

Taken together, we found the annual P surplus equilibrium is around 150  $\text{kg P}_2\text{O}_5 \text{ hm}^{-2}$  application rate ( $=65.5 \text{ P hm}^{-2}$ , Figure 1). Therefore, we decided to cut down the currently annual P fertilizer amount (180  $\text{kg P}_2\text{O}_5 \text{ hm}^{-2}$ ) of farmers (FFP) by 20% (FFP-20%P) and further substitute partial P with organic manure (FFPM-36%P).

### The Yield of Rice and Wheat Under Optimized P Fertilization

In the subsequent field trial from 2018 to 2019, we found that the application of P had a significant effect on rice yield compared to the no P application (NK) or no fertilization of N, P, K (CK) (Table 5). Reducing 20% P did not decrease the panicle number,



**FIGURE 3** | Variations in sequentially extracted P fractions under optimized fertilization on two-year rice-wheat rotation paddy field from 2018 to 2020.

grain number per panicle, thousand-grain weight, and seed setting rate, in comparison with the farmers' P fertilization rate (**Supplementary Table S3**). Combining data from the seasons revealed that the rice yield can be guaranteed by reducing at least 20% of the current P fertilization (**Supplementary Figure S1B**). Similar results were also found in wheat seasons. Application of P fertilizer strongly improved wheat yield (**Table 6**), with significantly increased panicle number and grain number per panicle (**Supplementary Table S4**). Compared to FFP, the yield of wheat in two seasons under FFP-20%P and FFPM-36%P treatments was similar and without the differences.

### P Uptake by Crops and P Surplus in the Rotation System Under Optimized P Fertilization

Optimized P fertilization in rice and wheat rotation showed reduced 20% P input did not cause a decrease in P uptake but significantly depressed the P surplus in comparison with the farmer's P fertilization dose (**Table 7**). It seemed that the uptake of P showed no difference between farmer's treatment (FFP) and reduced 20% P fertilizer treatments (FFP-20%P and FFPM-36%P). Furthermore, rice took up more P than wheat and caused a net deficit of P surplus. But taken together, the annual P surplus was near equilibrium under treatments of reduced 20% P fertilizer (FFP-20%P and FFPM-36%P).

### P Use Efficiency in Rice and Wheat Season

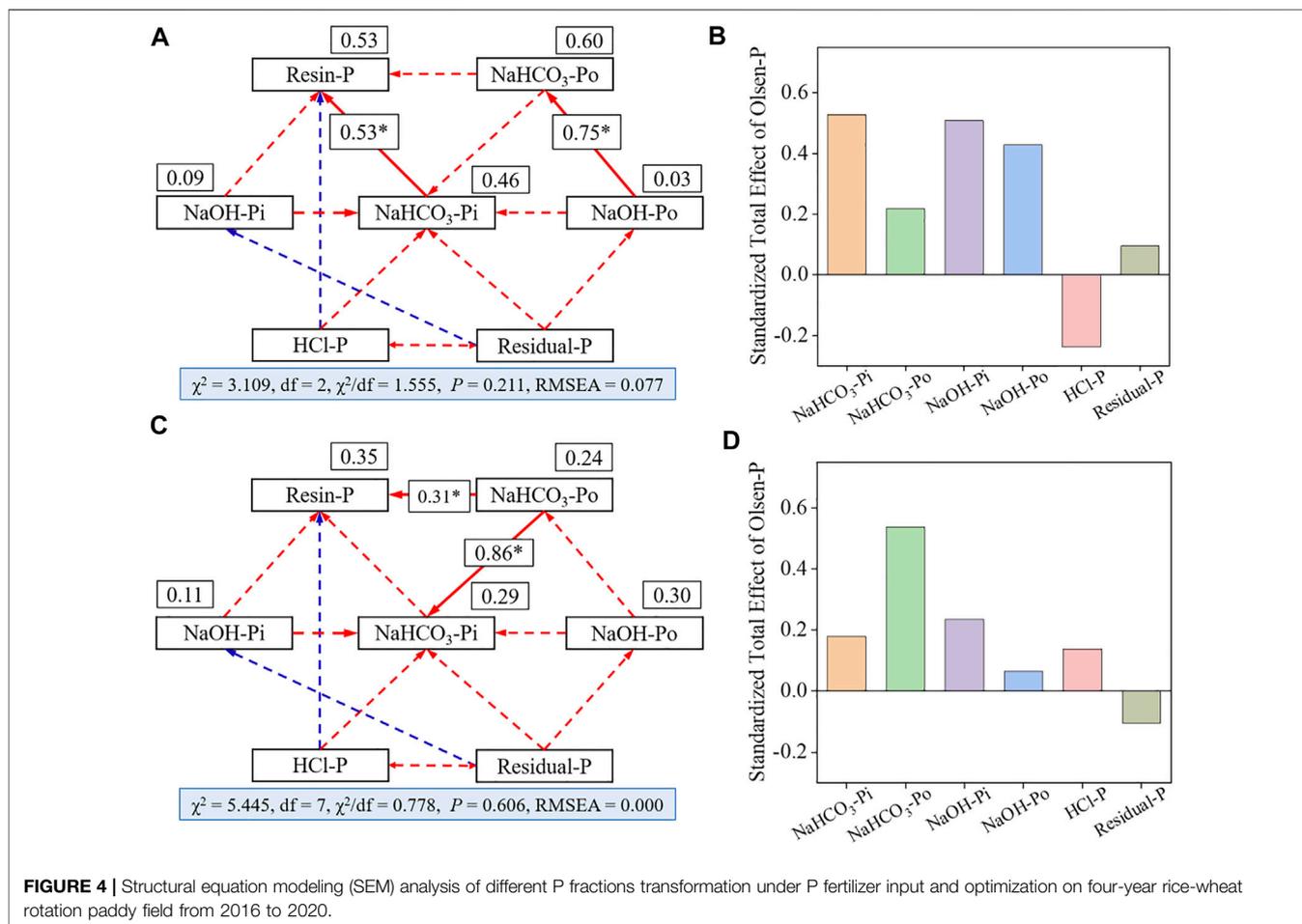
The effect of different P fertilizer application rates on the P use efficiency in rice and wheat rotation was calculated (**Table 8**). With elevated application rates of P fertilizer, the agronomic efficiency of P ( $AE_p$ ) continuously decreased, while the recovery efficiency of P ( $RE_p$ ) increased and reached a maximum under  $P_{75}$  treatment, and then decreased under  $P_{100}$  treatment for both rice and wheat season (**Table 8**).

The optimized P fertilization with 20% reduced P significantly enhanced the P use efficiency of  $AE_p$  and  $RE_p$  both in the rice and wheat season (**Table 9**). FFPM-36%P treatment had even higher  $AE_p$  and  $RE_p$  than FFP-20%P treatment, indicating that organic fertilizer could improve the P availability in soil compared with chemical fertilizer.

### Changes of P Fractions in Soil

Different P fractions were extracted from the soil after every season. P extracted with anion-exchange resin and  $NaHCO_3$  is considered labile P, and that extracted with NaOH is moderately labile P. P extracted with HCl and residual P is considered stable P (Hedley et al., 1982; Tiessen and Moir 1993).

After treatment of P fertilizer application rates, labile P and moderately labile P in soils were consequently elevated by the increase of P input, either in rice season (**Figures 2A,C**) or wheat season (**Figures 2B,D**). This is also true after the optimized fertilization treatments (**Figure 3**) that labile P and moderately labile P significantly increased, compared with no P treatments



(CK and NK). While organic P content and stable P content were not influenced by the input of P fertilizer in the field experiments.

Further SEM was used to explore how different P fertilizer input and optimization affected soil P fraction transformation. The results showed that  $\text{NaHCO}_3\text{-Pi}$  had a direct and positive effect on resin-P (path coefficient = 0.53);  $\text{NaOH-Po}$  has a direct and positive effect on  $\text{NaHCO}_3\text{-Po}$  (path coefficient = 0.75) (Figure 4A); among them,  $\text{NaHCO}_3\text{-Pi}$  (standard coefficient = 0.53) and  $\text{NaOH-Pi}$  (standard coefficient = 0.51) have the most significant influence on the total standard of resin-P (Figure 4B). In the experiment of optimization of P fertilization, the results showed that  $\text{NaHCO}_3\text{-Po}$  had a direct and positive effect on  $\text{NaHCO}_3\text{-Pi}$  (path coefficient = 0.86) and resin-P (path coefficient = 0.31) (Figure 4C). Among them,  $\text{NaHCO}_3\text{-Po}$  (standard coefficient = 0.55) has the most significant influence on the total standard of resin-P (Figure 4D).

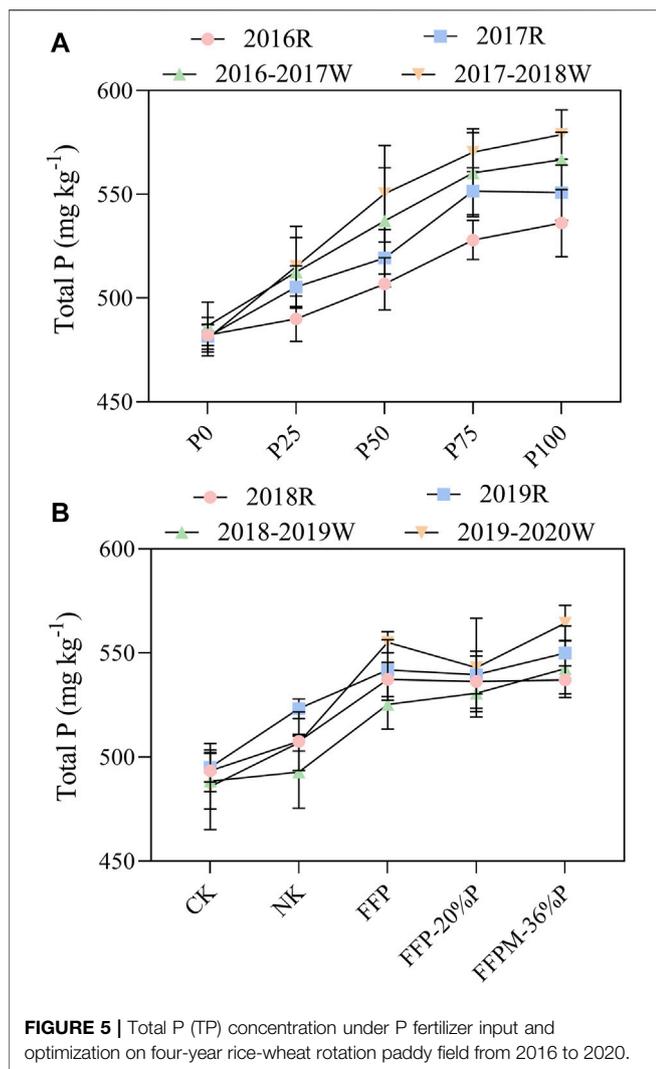
Taken together, the total P in the soil is strongly elevated by the input dose of P fertilizer (Figures 5A,B). Accordingly, soil Olsen-P content was significantly elevated with increasing P fertilizer application rates (Figures 6A,B). A positive correlation existed between the soil Olsen P content and the P input dose in both the rice and wheat seasons (Supplementary Figure S2).

## DISCUSSION

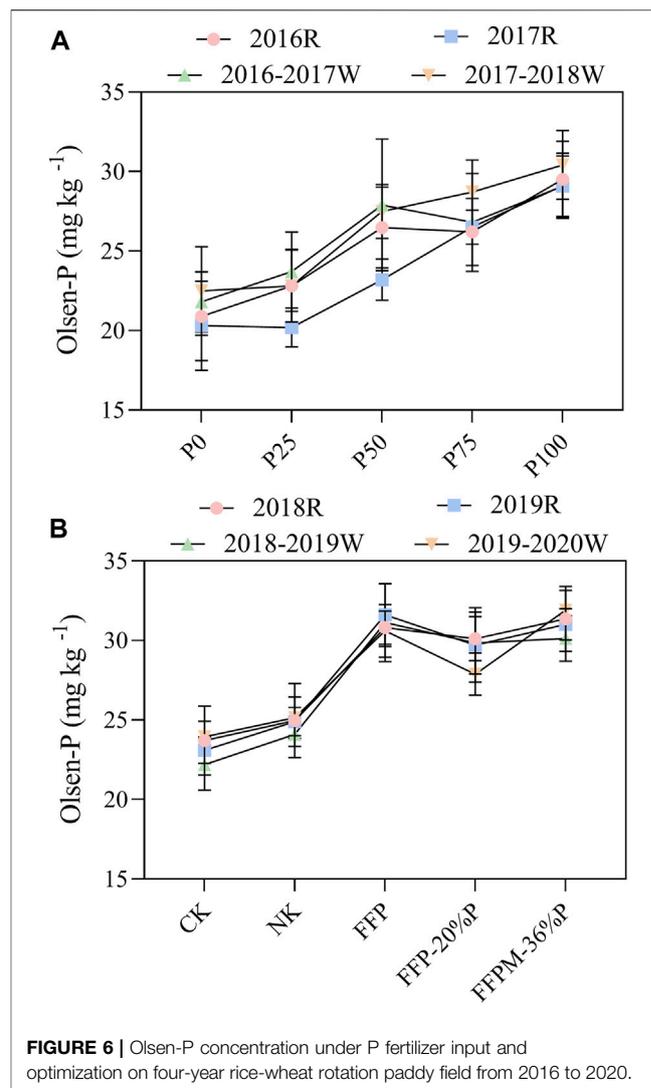
### Effects of P Fertilization Regimes on Crop Yield

Our field experiments showed that the application amount of P fertilizer had a major effect on the yields of rice and wheat (Tables 1, 2, Supplementary Figure S1), which was related to the formation of the panicle number of these crops (Supplementary Tables S1, S2). The results indicated that the response of the panicle number rather than grain weight to fertilization regimes is the crucial factor determining crop yield. This is consistent with various previous studies (Peng et al., 2007; Gao et al., 2009; Ding et al., 2013; Song et al., 2013).

However, crop yield could not cross the threshold of a P fertilizer amount. In our experiment,  $75 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$  input caused the maximum rice or wheat yield. Excessive application of P fertilizer could not further promote the crop yield in this area. (Supplementary Figure S1). Similar results were also found by other researchers (Gong et al., 2011; Li et al., 2015). It was explained that if the amount of P fertilizer exceeded the requirement of crop growth, excessive P would not further promote crop yield.



**FIGURE 5** | Total P (TP) concentration under P fertilizer input and optimization on four-year rice-wheat rotation paddy field from 2016 to 2020.



**FIGURE 6** | Olsen-P concentration under P fertilizer input and optimization on four-year rice-wheat rotation paddy field from 2016 to 2020.

In addition, we found that organic fertilizer replacing partial chemical fertilizer can ensure the panicle number and grain number of rice or wheat (**Supplementary Tables S1, S2**) necessary to achieve a similar or even higher yield like that under farmers' fertilization (**Tables 2, 3**), albeit not statistically significant (**Supplementary Figure S1**). The results here indicated that organic manure could replace some chemical P fertilizer to further cut down the input of P. The involved mechanism may be due to the activation of soil microorganisms to mobilize the otherwise unavailable P in soil (Kaur et al., 2008). Organic manures increased organic carbon and nitrogen contents in soil (Luo et al., 2019), which in turn could stimulate the abundance of microorganisms to promote the release of ALP and accelerate the transformation of P in soil (Xavier et al., 2009; Chen et al., 2022). In addition, organic matters could help form soil aggregates and improve the physical properties of soil (Ye et al., 2019). Thus, crop production could be improved by the addition of organic manures. It is also true that 28 years of organic-inorganic fertilization field trials showed that the rice yield was 19.9%

higher than that under chemical fertilization treatment (Huang et al., 2013).

## Effects of Different Fertilization Regimes on P Use Efficiency

Different inputs of P fertilizer had a positive effect on P uptake by crops (**Table 4**), which in turn increased the accumulation of P in crop biomass (Li et al., 2015). In this experiment, it was also found that applying too much P fertilizer did not further increase P accumulation in crops when the P input was over  $75 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$  (**Table 4**). Meanwhile, crop yield did not continue to increase when P input exceeded  $75 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$  (**Supplementary Figure S1**); this might have been caused by the limitation of other nutrients in the soil. Accordingly, the agronomy efficiency of P ( $AE_p$ ) decreased when the P input increased, but the recovery efficiency of P ( $RE_p$ ) reached maximum value under the treatment of  $75 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$  (**Table 8**). Our results indicated that  $75 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$  was

currently the optimum to meet the requirement of rice or wheat yield in Taihu Lake Basin with the highest P fertilizer use efficiency. In addition, the annual P surplus reached a level of equilibrium under the treatment of  $75 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$  for the rice season or the wheat season (Table 4 and Figure 1).

Therefore, to optimize P fertilization for local farmers in Taihu Lake Basin, we cut down 20% input of chemical P fertilizer used by farmers' ( $90 \text{ kg P}_2\text{O}_5 \text{ hm}^{-2}$ ) and tested it in field trials. The P uptake by crops was not disturbed by the 20% decrease in P fertilizer amount used by local farmers (Table 7); meanwhile, the P use efficiency was enhanced to different degrees by the FFP-20%P and FFP-36%P treatments, compared to the conventional FFP treatment. This also suggests that organic fertilizer might improve P fertilizer use efficiency (Ayaga et al., 2006).

## Effects of Different Fertilization Regimes on Soil P Pool

Fertilization is one of the major factors that can affect the various P fractions in the soil (Hong et al., 2015). Understanding the composition and transformation characteristics of soil P is of great significance for improving the recycling of P in soil (Wang et al., 2009). In this study, we analyzed P fractions extracted from the soil after harvest. The application of P fertilizer increased the total P content of the soil (Figures 5A,B) and mainly in inorganic P fractions of  $\text{NaHCO}_3\text{-Pi}$ , and  $\text{NaOH-Pi}$  (Figures 2, 3). According to the structural equation modeling analysis, all the P application treatments caused the transformation of moderately labile P ( $\text{NaOH-P}$ ) to labile P (Resin-P and  $\text{NaHCO}_3\text{-P}$ ) (Figure 4), which indicated that P application was beneficial to the mobilization of P (Chen et al., 2021; Chen et al., 2022). In this way, the Olsen-P content was significantly elevated by P fertilization (Figure 6). Our results showed that changes in soil P within a certain range were positively correlated with the amount of P fertilizer input. The content of Olsen-P in soil increased with the increase of the P application rates (Supplementary Figure S2). Our results were in line with other findings (Wang S. X. et al., 2012). In addition, some studies reported that P fertilization could also enhance the organic P in the soil due to the stimulation of microorganisms (Feng et al., 2010). However, our study did not detect significantly increased organic P content after P fertilization, which may be limited by C sources in the soil (Zhang et al., 2018).

Nevertheless, it could not be forgotten that crops also need to consume inorganic P from soil (Penuelas et al., 2013), whose root systems in soil could transfer moderately labile P from solid phase to liquid phase through abiotic or biological processes (Frossard et al., 2000), such as secretion of root exudates (Menezes-Blackburn et al., 2016; Zou et al., 2018; Chai and Schachtman, 2022) or microbial-related enzymes (Sinsabaugh et al., 2009; Nannipieri et al., 2011). Soil resin-P is a dynamic P pool and is easily absorbed by plants and utilized by soil microorganisms, which may also explain the reason why

Resin-P is relatively less than other P fractions and kept relatively constant under all treatments.

## CONCLUSION

In this study, P fertilization rates caused P surplus variability, providing solid evidence to guide the nutrition management for input and balance of P in the rice and wheat rotation system. Results of our field experiments showed that applying appropriate P fertilizer is not only important for the improvement of crop yields but also to keep a relatively higher PUE, which in turn can cut down the P accumulation in soil and alleviate the risk of P pollution in the ecosystem. Nevertheless, our research also proved that combining organic fertilizer with reducing P fertilizer can ensure crop yield and enhance the PUE of rice and wheat. Thus, our findings provided a basis for formulating efficient and reasonable P fertilizer optimization methods for the rice–wheat rotation system.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; and further inquiries can be directed to the corresponding authors.

## AUTHOR CONTRIBUTIONS

LX: Conceptualization, data curation, investigation, methodology, and writing—original draft. GC: Conceptualization, data curation, formal analysis, investigation, and writing. HW: Investigation, methodology, formal analysis, and writing—editing. YL conducted the field experiment. CL conducted the field experiment. LC: Software. YZ: Project leader and writing—review and editing. XX: Resources and writing—review and editing. WW: Review and editing.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.932833/full#supplementary-material>

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