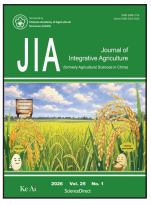
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RESEARCH ARTICLE

Sustainable phosphorus (P) management: Impact of low P input with enhancement measures on soil P fractions and crop yield performance on a calcareous soil

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Highlights

- A 20% P reduction with straw wrapping and ammonium sulfate instead of urea maintains crop yield while enhancing agronomic efficiency and partial factor productivity.
- Straw wrapping combined with ammonium sulfate boosts labile and moderately labile soil P fractions, optimizing P bioavailability and reducing environmental risks.
- The integrated management strategy provides a feasible path for sustainable P management.

Abstract

The continuous supply of phosphorus (P) is indispensable in crop production. However, P resources are non-renewable, and environmental concerns like eutrophication associated with its loss from agroecosystems make the sustainable management of P resources essential for ensuring global food security. This study was designed to reduce mineral P inputs through management practices. A field experiment comprising a wheat–maize rotation system was conducted in the Guanzhong Plain of Shaanxi Province, China from 2018–2023. The eight treatments included CK (without P), FP (conventional P application); RP (recommended P); RP_{80} (20% reduction in RP); SRP_{80} (20% reduction in RP with straw wrapping); ARP_{80} (20% reduction in RP with ammonium sulfate instead of urea); $SARP_{80}$ (20% reduction in RP with straw wrapping and ammonium sulfate instead of urea); and $SARP_{60}$ (40% reduction in RP with straw wrapping and ammonium sulfate instead of urea). Crop yield, P uptake, and P fertilizer use efficiency were measured during harvest and throughout the entire period of the study. At the end of the experiment, P fractions were estimated using the Tiessen-Moir P classification method. The results revealed that the grain yields of all the treatments except for RP_{80} were significantly increased compared to CK, with increases of 14.9–28.8%. Furthermore, agronomic efficiency, apparent P use efficiency, P recovery rate, and partial factor productivity were significantly improved for the treatments that received 20% less P with straw wrapping. Moreover, the enhancement measures significantly increased labile and moderately labile P in the soil. Therefore, straw wrapping with ammonium sulfate instead of urea is one of the most effective ways to reduce mineral P inputs while increasing the efficiency of P in wheat–maize rotation systems.

Keywords: sustainability, bioavailability, fertilization, phosphorus use efficiency, nutrient cycling

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1. Introduction

Phosphorus (P) is the second most vital plant nutrient after nitrogen. Its adequate supply ensures the fundamental processes of photosynthesis, flowering, fruiting and maturation in plants (Weil and Brady 2017). Therefore, maintaining a sufficient P level in the soil by adding fertilizers is essential, making P fertilizer an integrated component of agriculture. P fertilizers are derived from phosphate rock (PR), which is non-renewable and geographically restricted to a few countries (Scholz and Wellmer 2013; Cordell and White 2015), and 80% of PR is excavated for P fertilizer production (Ashley *et al.* 2011). Given the one-way flow of P from its reserves to waste dumps or water bodies, as suggested by the Green Revolution, the risk of P scarcity has increased, which may lead to a P crisis in the future (Gilbert 2009).

At the same time, the world population is growing quickly and is estimated to reach 10.3 billion by 2080 (United Nations 2024). This tremendous population growth suggests very intensive cultivation in the future because of the need to produce more food with the same area of land, which will further increase the P input rates, resulting in a greater burden on the limited PR reserves. Aside from the probable PR scarcity, another important issue associated with P fertilization is that only 10–25% of applied P is used by the plants, whereas the substantial remaining amount is fixed by the soil. This soil-bound P later ends up in aquatic systems, and the excessive discharge of P into water is a leading cause of the serious environmental problem of eutrophication (Liu *et al.* 2015; Wang S D *et al.* 2018; Zheng *et al.* 2020). Therefore, paying attention to the transformation of applied P to various fractions in the soil is of great significance for reducing its accumulation and ensuring that only the requisite amount is supplied to the crops.

The share of different soil P fractions is known to determine the amount of P available for uptake by crops (Rose *et al.* 2010; Wang *et al.* 2012; Bol *et al.* 2016). These fractions can be grouped into three pools (occluded P, moderately labile P, and labile P) based on Hedley's classification method (Yang and Post 2011). When P is applied to soil, the pool it enters may be largely determined by management practices (Zhang *et al.* 2024). A comprehensive path analysis was used to develop the link between P application measures on both its fractions and availability, and management strategies were found to be effective for manipulating the P fractions in soil (Tiecher *et al.* 2018). The impact of long-term inorganic fertilization on P fractions was found to promote the accumulation of inorganic P in the soil and increase the risk of P loss (Xu *et al.* 2022). The judicious application of P can reduce its losses and improve its rate of utilization by crops (Gong *et al.* 2024). Studies have found that a reduced application of P combined with rational management strategies improved P utilization without impacting the crop yield (Jagdeep and Brar 2022; Li *et al.* 2023). Furthermore, straw return was found to influence soil phosphatase activity, reduce P fixation by soil minerals, and promote P uptake by crops (Li *et al.* 2022; Tang *et al.* 2024). In addition, using acidic N fertilizer along with P fertilizer was also found to reduce soil pH, lower P fixation, and promote P availability in calcareous soils (Jing *et al.* 2010; Ma *et al.* 2014). Therefore, comprehensive P management strategies should be devised for the optimum application of P so that it can be managed sustainably.

Studies on the sustainable use of P through management strategies are currently underway. However, how much P input can be reduced through management practices and what happens when multiple management practices are coupled to maximize their advantages remain unexplored areas in this field. Therefore, the present study examined the effects of reduced mineral P input through straw wrapping of P fertilizer along with the application of acidic N fertilizer.

We hypothesized that the reduction in mineral P input with straw wrapping and ammonium sulfate (physiologically acidic N fertilizer) instead of urea favors the labile P pool to sustain an optimum supply of P to crops, resulting in a good crop yield even at lower P input rates. The specific objective of this study was to explore the relationships between soil P fractions, available P, and crop yield under reduced P applications to create a theoretical foundation for the rational application of P in agroecosystems.

2. Materials and methods

2.1. Site description

From 2018–2023, a field experiment was conducted at Wuquan Town (108°00′E, 34°18′N), Yangling, in Guanzhong Plain of Shaanxi Province, China. The climate at the site is classified as a warm temperate semi-humid continental monsoon climate with an average annual temperature of 12.9°C and average annual precipitation of 550–600 mm. This area encounters high rainfall from June to September. The average annual evaporation is about 993 mm, and the frost-free period is 184–216 days. The soil type is Terric Anthrosols (IUSS Working Group WRB 2022). Before the experiment, the soil (0–20 cm soil layer) was sampled to assess some selected chemical properties, and the data are presented in Table 1.

2.2. Experimental design

The experiment involved a winter wheat and summer maize rotation system, which started in October 2018 and continued until October 2023. Eight treatments were laid out in a randomized complete design with three replicates, and each plot was spread across an area of 28 m^2. The treatments included: control (CK, no P application); conventional P rate (FP, 180 kg P_2O_5 ha^{-1}); recommended P rate (RP, 120 kg P_2O_5 ha^{-1}); 20% reduction of RP

Table 1 Selected chemical properties of the experimental soil

Chemical property	Value
pH	8.30
Organic matter (g kg^{-1})	10.4
Total nitrogen (g kg^{-1})	0.56
Total phosphorus (g kg^{-1})	0.84
Ammonium nitrogen (mg kg^{-1})	2.6
Nitrate nitrogen (mg kg^{-1})	10.7
Available phosphorus (mg kg^{-1})	12.3
Available potassium (mg kg^{-1})	106

(RP_{80}, 96 kg P_2O_5 ha^{-1}); 20% reduction of RP with straw wrapping (SRP_{80}); 20% reduction of RP with ammonium sulfate instead of urea (ARP_{80}); 20% reduction of RP with an integrated measure of straw wrapping and ammonium sulfate instead of urea ($SARP_{80}$); and 40% reduction of RP with the integrated measure ($SARP_{60}$, 72 kg P_2O_5 ha^{-1}). All fertilizers were applied at sowing. The amounts and methods used for applying N fertilizer and calcium superphosphate (P fertilizer source) are given in Table 2. Note that potassium was not added as the experimental soil was rich in potassium (Table 1). Moreover, during the growing season of wheat, each plot was divided into 14 rows for the sowing of seeds, while for maize, each plot was divided into seven rows, and all other agronomic practices were kept constant for each treatment and carried out according to the practices of local farmers.

2.3. Crop harvest, yield and P use efficiency

Wheat and maize were harvested throughout the experiment to record yield and relevant traits. Briefly, wheat was harvested by cutting the aboveground part after selecting the middle four rows from each plot, while three middle rows were selected for maize. After harvest, the fresh and dry weights were recorded for the wheat and maize crops, followed by determining the P contents in both straw and grain. The average annual yield was estimated by taking the average yield of both crops per year up to the end of the experiment. Furthermore, the efficiency of P input in response to reduced P application along with the enhancement measure was determined using the following equations:

$$PU=(P\text{ in grain}\times\text{Grain yield})+(P\text{ in straw}\times\text{Straw yield}) \quad (1)$$

$$PRR=\frac{PU}{P\text{ rate}}\times 100 \quad (2)$$

$$APU=\frac{(PU\text{ in P application area})-(PU\text{ in CK})}{P\text{ rate}}\times 100 \quad (3)$$

$$PFP=\frac{\text{Grain yield in P application area}}{P\text{ rate}}\times 100 \quad (4)$$

$$AE=\frac{(\text{Grain yield in P application area})-(\text{Grain yield in CK})}{P\text{ rate}}\times 100 \quad (5)$$

where PU is P uptake (kg ha^{-1}), PRR is P recovery rate (%), APU is apparent P use efficiency (%), PFP is partial factor productivity (kg kg^{-1}), AE is agronomic efficiency (kg kg^{-1}), and CK represents the control treatment. The PU values from eq. (1) were used to calculate PRR and APU in eqs. (2) and (3), respectively.

2.4. Soil sampling and analysis

In October 2023, following five years of experimental treatments, soil samples were taken to measure the P fractions. Soil P content was classified using the Hedley P classification method, which was refined by Tissen (1984) through the following steps. A clean 50 mL centrifuge tube was filled with a 100-mesh sieved soil sample weighing 0.5 g. Then 30 mL of deionized water and two HCO_3^- saturated Resin films were added, and the molybdenum antimony resistance colorimetric method was used to determine the amount of water-soluble P, or Resin-Pi. Next, the samples were extracted with 0.5 mol L^{-1} $NaHCO_3$, 0.1 mol L^{-1} NaOH, 1 mol L^{-1} HCl (the diluted HCl), the concentrated HCl heating in a water bath, and then digested the residual-P with H_2SO_4-H_2O_2, successively. The P contents of all extracts were determined by the molybdenum-antimony resistance calorimetric method. The two fractions extracted by the diluted and concentrated HCl were referred to as D.HCl-Pi and C.HCl-P, respectively.

2.5. Statistical analysis

The data were statistically analyzed to determine the significant differences between treatments using one-way analysis of

Table 2 Detailed information about fertilizer application with management measures[1)]

Treatment[2)]	P_2O_5 rate (kg ha^{-1})		Mode of fertilizer application
	Summer maize[3)]	Winter wheat[4)]	
CK	0	0	No P application, N was broadcasted into the soil with a plough.
FP	45	135	Conventional application of P as per the practice of the local farmers, N and P fertilizers were spread after ploughing into the soil before seed sowing.
RP	30	90	Recommended doses of P were used, and N and P fertilizers were spread after ploughing into the soil before seed sowing.
RP_{80}	24	72	The recommended dose of P was reduced by 20%, and both N and P fertilizers were applied in ditches between the rows.
SRP_{80}	24	72	Fertilizers were sandwiched between two layers of wheat straw. For this, wheat straw was uniformly distributed into the ditches, followed by the addition of the fertilizers and then covered with the remaining straw. The wheat straw was applied at 1,500 kg ha^{-1} for all the treatments receiving wheat straw.
ARP_{80}	24	72	All consistent with treatment RP_{80} except for the N source (urea), which was replaced with ammonium sulfate.
$SARP_{80}$	24	72	All consistent with treatment SRP_{80} except for the N source (urea), which was replaced with ammonium sulfate.
$SARP_{60}$	18	54	All consistent with treatment $SARP_{80}$ except for the reduction of the P dose, which was reduced by 40% for this treatment.

[1)] Straw wrapping of fertilizers with ammonium sulfate instead of urea; the straw used in the experiment contained 0.37 g kg^{-1} P.
[2)] CK, control; FP, conventional P; RP, recommended P; RP_{80}, 20% reduction in RP; SRP_{80}, 20% reduction in RP with straw wrapping; ARP_{80}, 20% reduction in RP with ammonium sulfate; $SARP_{80}$, 20% reduction in RP with straw wrapping and ammonium sulfate; $SARP_{60}$, 40% reduction in RP with straw wrapping and ammonium sulfate.
[3)] Each treatment received the same amount of N fertilizer for summer maize (187.5 kg ha^{-1}).
[4)] Each treatment received the same amount of N fertilizer for winter wheat (165 kg ha^{-1}).

variance (ANOVA). The least significant differences (LSD) test was also applied to the treatment means to determine which mean groups differ from each other (P<0.05). The relationships of Olsen-P, crop yield, and P uptake with soil P fractions and P pools were determined using correlation analysis and the structural equation model. Origin 2021 software was mainly used for data visualization, and all the statistical analyses were performed with SPSS 20.

3. Results

3.1. Effect of P fertilizer reduction with enhancement measures on P use efficiency

The apparent P use efficiency (APU) showed great variation across the treatments (Table 3). The highest APU was recorded for $SARP_{80}$, although it was not significantly different from $SARP_{60}$, whereas the lowest APU values were recorded for FP and RP_{80} with no significant difference between them. Between these two extremes, the intermediate APU values were for SRP_{80} and ARP_{80}, but there was no significant difference between them. They did not show any significant difference compared with $SARP_{60}$, but both showed significant differences when compared with FP and RP_{80}.

The P recovery rate (PRR) showed great variation among the treatments. The highest PRR (148.5%) was recorded for SARP60 (Table 3), which was significantly different from the other treatments. Moreover, both RP and RP_{80} showed high PRR compared to FP, but they were not significantly different. When compared with SRP_{80}, ARP_{80}, and $SARP_{80}$, FP and RP_{80} showed significantly lower PRR values. However, SRP_{80}, ARP_{80}, and $SARP_{80}$ did not show any significant differences between them.

Partial factor productivity (PFP) was the highest for $SARP_{60}$ and the lowest for FP (Table 3). $SARP_{80}$ had higher PFP values than SRP_{80}, but the values for these two treatments were not significantly different. Moreover, there was no significant difference between RP_{80} and ARP_{80}, but ARP_{80} showed a slightly higher value for PFP. Furthermore, the PFP value for RP was significantly higher than FP, but it was significantly lower than the other treatments.

For agronomic efficiency (AE), $SARP_{80}$ showed the highest AE values. However, it was not significantly different from RP, SRP_{80}, or $SARP_{60}$ (Table 3). The lowest AE value was recorded for RP_{80}, but it was not significantly different from FP.

Table 3 Effect of reduced P application with application measures on P use efficiency[1)]

Treatment[2)]	APU (%)	PRR (%)	PFP (kg kg^{-1})	AE (kg kg^{-1})
FP	29.6±4.2 c	69.2±6.2 d	272.0±0.8 f	47.0±0.8 cd
RP	41.9±2.4 b	97.3±6.7 c	406.8±12.6 e	69.2±12.6 abc
RP_{80}	26.6±1.9 c	101.7±5.4 c	449.8±23.9 d	27.9±23.9 d
SRP_{80}	43.3±6.3 b	116.8±2.2 b	504.1±15.9 bc	82.1±15.9 abc
ARP_{80}	41.3±3.8 b	112.7±0.9 b	481.6±9.3 cd	59.6±9.3 bcd
$SARP_{80}$	59.0±6.9 a	112.0±2.4 b	536.3±7.2 b	101.5±7.2 a
$SARP_{60}$	49.1±10.4 ab	148.5±3.3 a	655.4±45.1 a	92.8±45.1 ab

[1)] APU, apparent P use efficiency; PRR, P recovery rate; PFP, partial factor productivity; AE, agronomic efficiency.
[2)] FP, conventional P; RP, recommended P; RP_{80}, 20% reduction in RP; SRP_{80}, 20% reduction in RP with straw wrapping; ARP_{80}, 20% reduction in RP with ammonium sulfate; $SARP_{80}$, 20% reduction in RP with straw wrapping and ammonium sulfate; $SARP_{60}$, 40% reduction in RP with straw wrapping and ammonium sulfate.
Data are mean±SD (n=3) for P efficiency from 2018–2023. Treatments were compared using one-way ANOVA, and LSD was applied to identify differences between the mean groups. Different lowercase letters indicate significant differences between means (P<0.05).

3.2. Effect of P fertilizer reduction with enhancement measures on crop yield

The average annual yield data revealed that each P treatment significantly increased the grain yield compared to CK, except in 2019, when the P reduction without straw return resulted in lower yields (Fig. 1-A). However, at the end of the experiment, the grain yield of $SARP_{80}$ reached the highest level, while the grain yield of the FP treatment was the highest in other years. Except for $SARP_{80}$, the grain yields of the other treatments showed trends of increasing at first and then decreasing in successive years.

The results of the cumulative annual average yield revealed that except for RP_{80}, the grain yields of all other treatments were significantly higher than that of CK, with average yield increases ranging from 14.9–28.8% (Fig. 1-B). The highest grain yields were recorded for FP and RP, but these two treatments were not significantly different. Furthermore, slight reductions in grain yield were recorded for SRP_{80} and $SARP_{80}$ compared to FP and RP. However, there were no significant differences between these four treatments. Also, no significant differences between SRP_{80}, $SARP_{80}$ and ARP_{80} were recorded, but the grain yields were slightly higher for the treatments receiving straw wrapping.

3.3. Effect of P fertilizer reduction with enhancement measures on total P, available P and soil pH

There were significant variations in the total P contents between different P treatments (Fig. 2-A). The highest total P content was found in the FP treatment soil, which was much greater than those of other treatments. Similarly, when the P rate was reduced by 20% based on RP, no significant differences were found between $SARP_{80}$, SRP_{80}, ARP_{80}, and RP_{80}. However, despite the reduction in P, the total P content remained above the baseline value of 840 mg kg^{-1} (Table 1).

Furthermore, a similar trend was observed for soil Olsen-P, with the FP treatment having the highest Olsen-P content (Fig. 2-A). However, the $SARP_{80}$, SRP_{80}, and ARP_{80} treatments showed higher values for Olsen-P than RP_{80} and $SARP_{60}$, although they did not differ significantly based on the same RP 20% reduction in the P rate. Also, despite the reduction in P dosage, the Olsen-P contents remained above the baseline value of 12.3 mg kg^{-1} (Table 1).

For soil pH, the treatments that received ammonium sulfate instead of urea ($SARP_{80}$ and $SARP_{60}$) showed lower values than all other treatments (Fig. 2-B). The pH of the soil treated with ARP_{80} was marginally higher than those of $SARP_{80}$ and $SARP_{60}$ but lower than those of CK, FP, RP, and RP_{80}.

3.4. Effect of P fertilizer reduction with enhancement measures on soil P fractions

Fig. 3-A–C illustrate how the reduced P application with

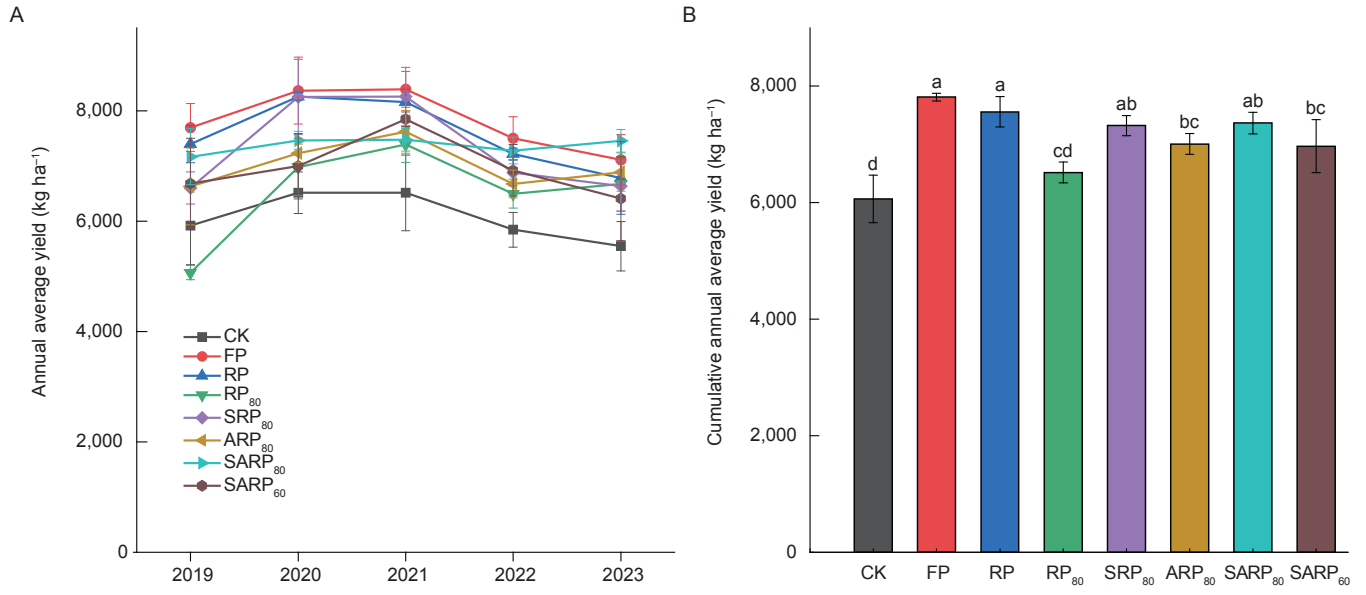


Fig. 1 Effects of reduced P application with enhancement measures on annual average yield (A) and cumulative annual average yield (B). CK, control; FP, conventional P; RP, recommended P; RP_{80}, 20% reduction in RP; SRP_{80}, 20% reduction in RP with straw wrapping; ARP_{80}, 20% reduction in RP with ammonium sulfate; $SARP_{80}$, 20% reduction in RP with straw wrapping and ammonium sulfate; $SARP_{60}$, 40% reduction in RP with straw wrapping and ammonium sulfate. Data are mean±SD (n=3). LSD was used to compare the means, and means with different letters are significantly different from each other (P<0.05), while the bars represent standard deviations in both figures (n=3).

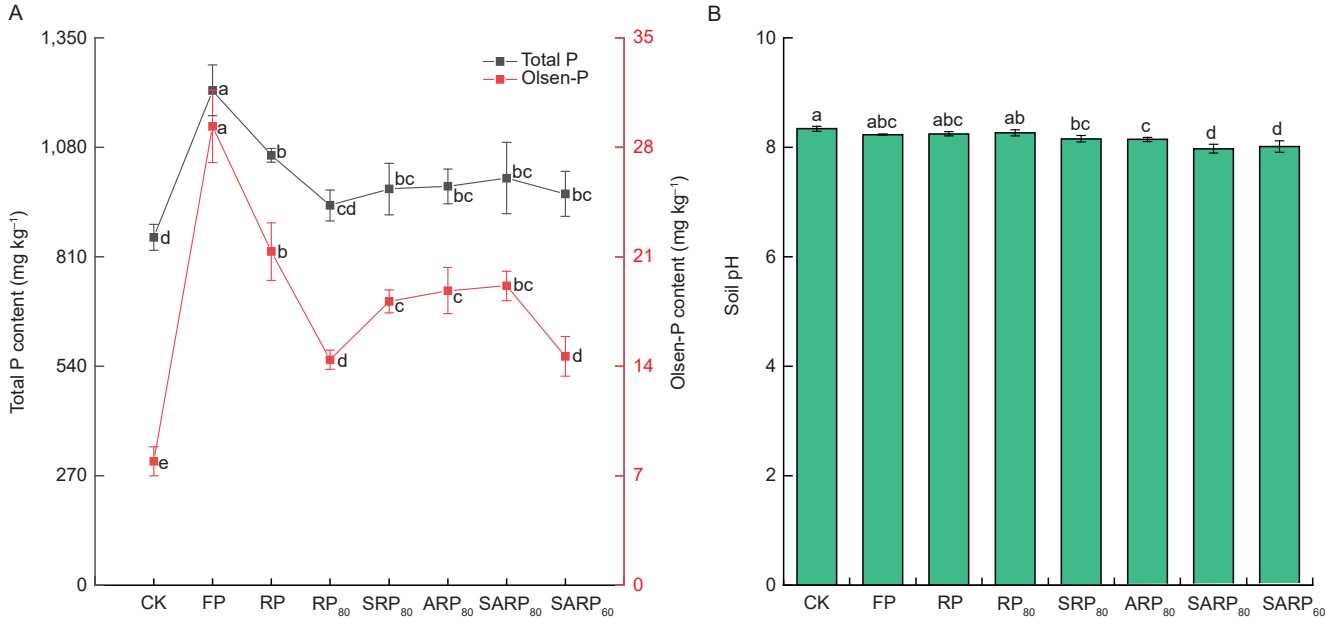


Fig. 2 Effects of reduced P application with enhancement measures on total P and Olsen-P (A) and pH (B). CK, control; FP, conventional P; RP, recommended P; RP_{80}, 20% reduction in RP; SRP_{80}, 20% reduction in RP with straw wrapping; ARP_{80}, 20% reduction in RP with ammonium sulfate; $SARP_{80}$, 20% reduction in RP with straw wrapping and ammonium sulfate; $SARP_{60}$, 40% reduction in RP with straw wrapping and ammonium sulfate. Data are mean±SD (n=3). LSD was used to compare the means, and means with different letters are significantly different from each other (P<0.05), while the bars represent standard deviations in both figures (n=3).

enhancement measures altered labile P fractions following five years of continuous fertilization. The highest value for Resin-Pi was 19.4 mg kg^{-1} in the FP treatment (Fig. 3-A), which was significantly different from the other treatments. The second most significant difference was recorded for $SARP_{80}$, which was significantly different from the CK and the other treatments. Regarding Resin-Pi, the remaining treatments (RP, RP_{80}, SRP_{80}, ARP_{80}, and $SARP_{60}$) showed some variations, with RP showing the highest value among them, but there were no significant differences. Similarly, for $NaHCO_3$-Pi, the FP treatment had the highest value (99.7 mg kg^{-1}) (Fig. 3-B), which was significantly different

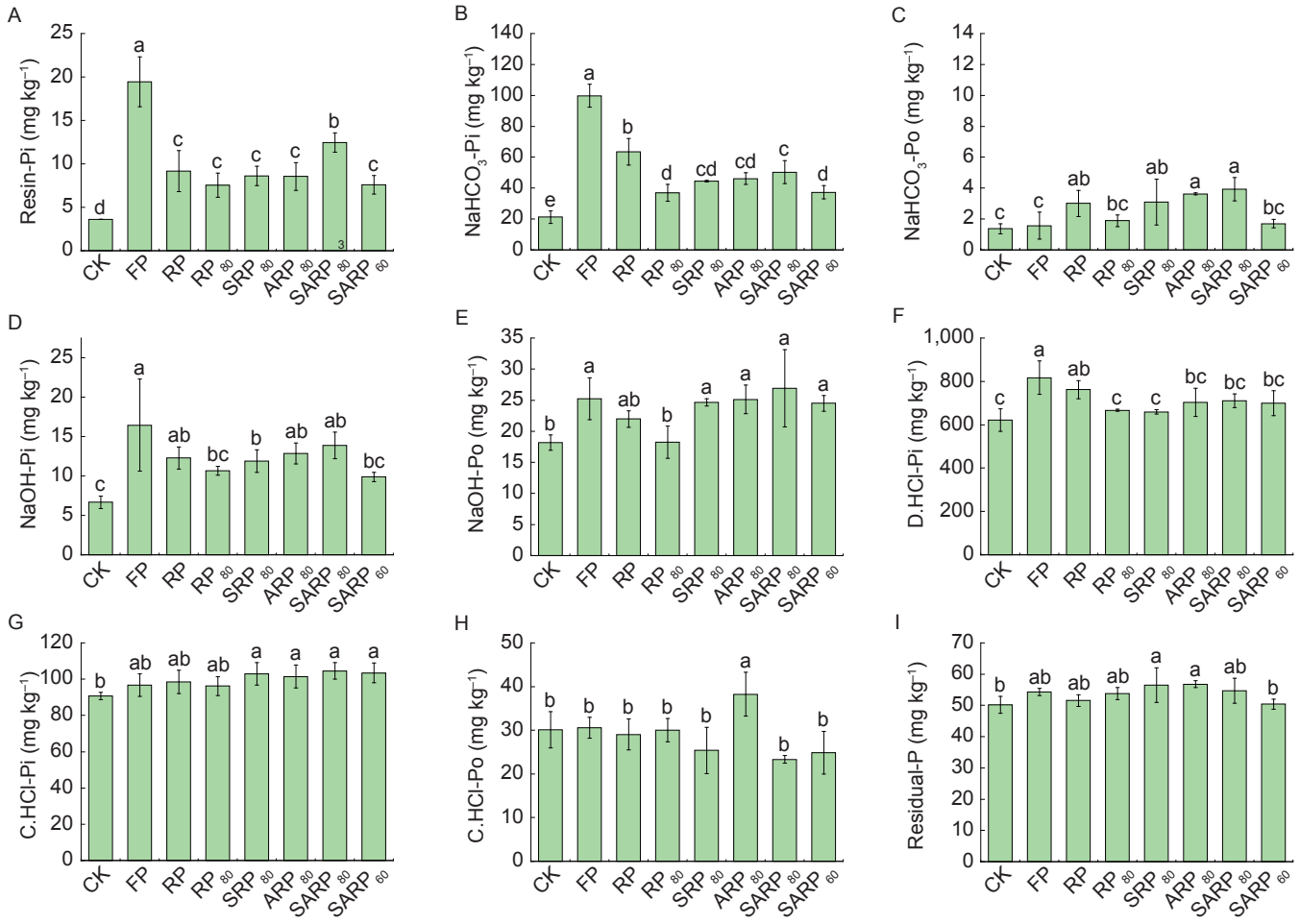


Fig. 3 Effects of reduced P application with enhancement measures on soil P fractions. A–C, labile P. D–F, moderately labile P. G–I, occluded P. CK, control; FP, conventional P; RP, recommended P; RP$_{80}$, 20% reduction in RP; SRP$_{80}$, 20% reduction in RP with straw wrapping; ARP$_{80}$, 20% reduction in RP with ammonium sulfate; SARP$_{80}$, 20% reduction in RP with straw wrapping and ammonium sulfate; SARP$_{60}$, 40% reduction in RP with straw wrapping and ammonium sulfate; Pi, inorganic P; Po, organic P. Data are mean±SD (n=3). LSD was used to compare the means, and means with different letters are significantly different from each other (P<0.05), while the bars represent standard deviations in both figures (n=3).

from the other treatments as well as the CK. Moreover, the second most significant value was recorded for RP, which was significantly different from the CK as well as all other treatments except for FP. The remaining treatments (RP$_{80}$, SRP$_{80}$, ARP$_{80}$, SARP$_{80}$, and SARP$_{60}$) were not significantly different from each other, however, SARP$_{80}$ had the highest value for NaHCO$_3$-Pi among them. Furthermore, NaHCO$_3$-Po showed the highest value for SARP$_{80}$, which was statistically different from the CK and FP, but not from RP, SRP$_{80}$, or ARP$_{80}$ (Fig. 3-C).

For moderately labile P (Fig. 3-D–F), after five years of fertilization, the values for NaOH-Pi ranged from 6.7–16.4 mg kg^{-1} (Fig. 3-D). The highest value was recorded for FP, which was significantly different from CK as well as the remaining treatments. However, among the treatments that received 20% less P, SARP$_{80}$ showed a slightly higher value for NaOH-Pi than ARP$_{80}$, SRP$_{80}$, RP$_{80}$, and SARP$_{60}$, but the differences among them were not statistically significant. Furthermore, for NaOH-Po, SARP$_{80}$ had the highest value, which was significantly higher than CK and the RP$_{80}$ treatment (Fig. 3-E). For the treatments with reduced P fertilizer, NaOH-Po at SARP$_{80}$ was slightly higher than at ARP$_{80}$, SRP$_{80}$, and SARP$_{60}$, but they were not significantly different from each other. The lowest value for NaOH-Po was recorded for RP$_{80}$. Moreover, D.HCl-Pi ranged in concentration from 621.9–816.9 mg kg^{-1}, which was also the highest for FP, and it was significantly different from CK as well as the other treatments except for RP (Fig. 3-F). However, the treatments that received a reduced P dose did not show any significant differences between them.

Limited variation was recorded in the occluded P after five years of continuous fertilization (Fig. 3-G–I). The contents of C.HCl-Pi ranged from 90.7–104.5 mg kg^{-1}, with the highest value recorded for SARP$_{80}$, which was significantly different from CK but not from the other treatments (Fig. 3-G). Regarding C.HCl-Po, the most significant value was recorded for ARP$_{80}$, which was statistically different from all the other treatments. In contrast, the remaining treatments were not significantly different from each other (Fig. 3-H). Similarly, the content of residual-P was the highest for ARP$_{80}$, although it was not statistically different from the other treatments except for CK and SARP$_{60}$ (Fig. 3-I).

3.5. Effect of P fertilizer reduction with enhancement measures on the percent shares of soil P fractions in topsoil

D.HCl-Pi ranged from 70.3–73.7% and accounted for the largest proportion of total P under each treatment (Fig. 4-A). The proportions of moderately labile P to total P were also the highest, with the variation ranging from 73.9–76.3% (Fig. 4-B). Compared with CK, all other fertilization treatments showed significant increases in the proportions of labile P, with the largest increase in FP. Of the reduced P application treatments, $SARP_{80}$ showed significantly higher values compared with RP_{80}, but no significant differences were found when compared with SRP_{80} or ARP_{80}.

3.6. Correlations between soil P fractions, crop yield and P uptake under reduced P application with enhancement measures

Strong positive correlations were clearly recorded for Resin-Pi with $NaHCO_3$-Pi, NaOH-Pi, D.HCl-Pi, LP, M-LP (P<0.01), and NaOH-Po (P<0.05), but NaOH-Po was not strongly correlated compared to the other fractions (Fig. 5). Based on Mantel's P-value (<0.01) and Mantel's r-value (≥0.4), the yield, Olsen-P, and P uptake also showed strong positive correlations with Resin-Pi. $NaHCO_3$-Pi was positively correlated with NaOH-Pi, D.HCl-Pi, LP and M-LP (P<0.01), with similar stronger correlations with yield, Olsen-P and P uptake as in the case of Resin-Pi. Conversely, $NaHCO_3$-Po showed significant correlations with some of the P fractions but weak correlations with yield (P≥0.05, r=0.2–0.4) and P uptake (P≥0.05, r<0.2) based on Mantel's P- and r-values. However, no relationship was noted for $NaHCO_3$-Po with Olsen-P. Furthermore, strong positive correlations were recorded between NaOH-Pi with D.HCl-Pi, LP and M-LP (P<0.01). These fractions also revealed strong positive correlations with yield, Olsen-P and P uptake. In contrast, NaOH-Po showed moderate correlations with P fractions, yield and Olsen P. However, it showed a strong positive correlation with P uptake (P<0.01, r≥0.4). Moreover, D.HCl-Pi had strong positive correlations with LP, M-LP, yield, Olsen-P and P uptake. C.HCl-Pi was significantly positively correlated with OP and Residual-P, and it showed moderate correlations with yield, Olsen-P and P uptake. Conversely, C.HCl-Po had a moderate correlation with OP, but it did not show any significant correlations with yield, Olsen-P or P uptake. Residual-P did not show any significant correlations with most of the P fractions nor with yield, Olsen-P or P uptake, while LP and M-LP revealed strong positive correlations with yield, Olsen-P and P uptake.

3.7. Structural equation model (SEM) for the relationships between P fractions, crop yield and P uptake

SEM analysis revealed that crop yield, P uptake, Olsen-P and soil P fractions were closely associated under the influence of enhancement measures (i.e., straw wrapping and ammonium sulfate instead of urea) (Fig. 6). The straw-returning measure had a direct impact (0.304) on NaOH-P. Similarly, NaOH-P significantly influenced (0.722) $NaHCO_3$-P. Resin-P and Olsen-P were significantly affected by $NaHCO_3$-P (1.016 and 0.902, respectively), and Olsen-P also showed direct effects on crop yield and P uptake (1.015 and 0.448, respectively). Moreover, crop P uptake was significantly affected by ammonium sulfate rather than urea (0.165). Residual-P had a direct effect on NaOH-P (0.264), and HCl-P had a direct effect on NaOH-P (0.647). Overall, occluded P might be transformed into moderately labile P and then moderately labile P into labile P, which would affect the Olsen-P content, thus affecting crop yield and P uptake under the enhancement measures.

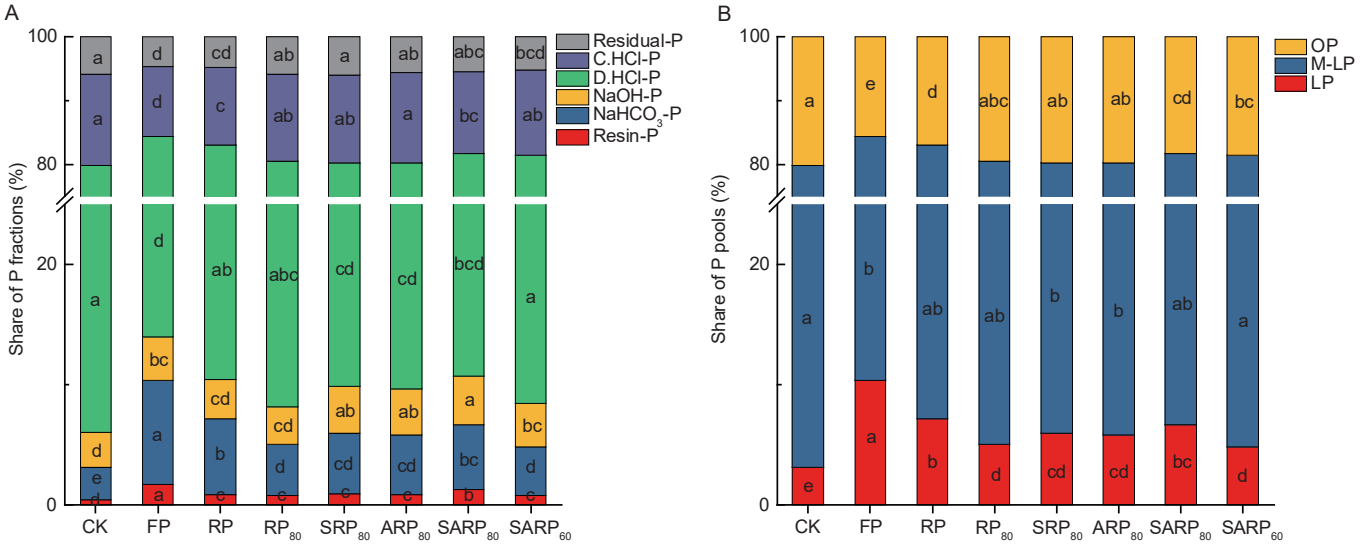


Fig. 4 Effects of reduced P application with enhancement measures on the percent share of soil P fractions (A) and soil P pools (B). CK, control; FP, conventional P; RP, recommended P; RP_{80}, 20% reduction in RP; SRP_{80}, 20% reduction in RP with straw wrapping; ARP_{80}, 20% reduction in RP with ammonium sulfate; $SARP_{80}$, 20% reduction in RP with straw wrapping and ammonium sulfate; $SARP_{60}$, 40% reduction in RP with straw wrapping and ammonium sulfate. Data are mean values compared using LSD, and means with different lowercase letters are significantly different from each other (P<0.05).

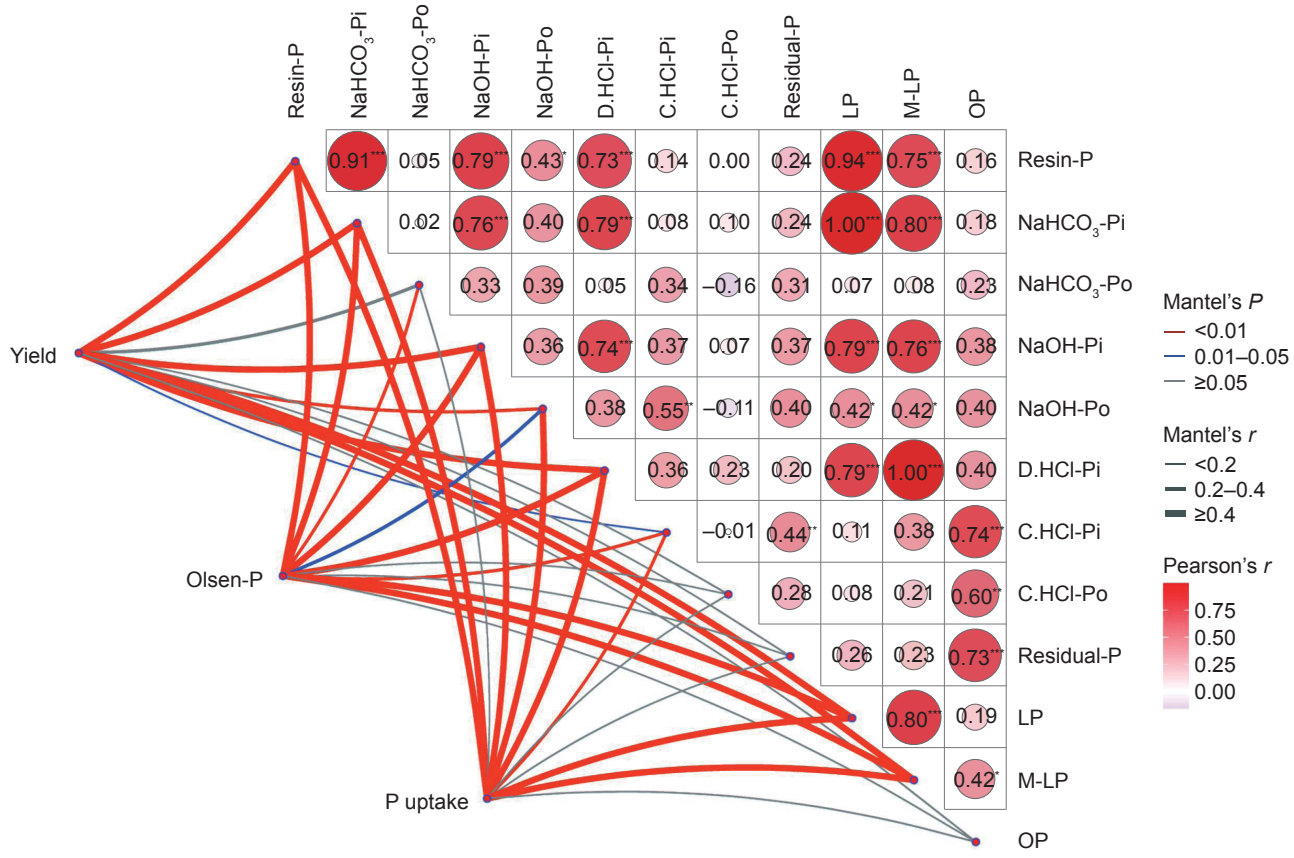


Fig. 5 Heatmap representing the correlations of yield, Olsen-P, and P uptake with different P fractions as well as P pools under the influence of reduced P application with enhancement measures. LP, labile P; M-LP, moderately labile P; OP, occluded P.

4. Discussion

4.1. Varying responses of crop yield and P efficiency to P with enhancement measures

Guanzhong Plain is the main grain-producing area in Shaanxi Province. Currently, the available P content in the soil has exceeded the critical value of available P for major crops (Tang *et al.* 2009; Bai *et al.* 2013), and continuing P application in the same fashion has reduced the utilization of P as no obvious improvement in yield has been reported. This study found that reducing FP to RP without any additional measures resulted in good crop yields, indicating that the current P use practice resulted in a considerable loss of applied P. Furthermore, based on the findings of this study, RP can be further reduced by 20% along with management strategies without compromising crop yield. However, a reduction in the RP dose by 20% without additional measures led to a significant reduction in crop yield (Fig. 1-A and B). The findings of this study are consistent with a meta-analysis of 522 field experiments regarding P fertilizer inputs along with different management practices (Wang *et al.* 2023). That study found that the judicious application of P fertilizer not only effectively improved crop yields but also reduced P losses, and straw return was the most effective technique for reducing those losses (Wang *et al.* 2023). Generally, the continuous application of P fertilizer at higher rates is believed to sustain high crop yields. However, in the Guanzhong Plain, the current farmers' practice is not effective, as an optimum yield can be achieved by reducing the P input along with management practices, which is an effective way to counter excessive P accumulation.

Furthermore, in the Guanzhong area, P fertilizers are applied through broadcasting under conventional farming, but studies have established that this is not an effective fertilizer application method (Demisie 2018). However, in the current study, since FP exceeds the amount required by the crop, the P input rate at RP met the needs of crop production even when using the same spreading technique. However, the effect might be more pronounced if strip application is used because the APU, PRR and PFP were significantly improved for the treatments where even the recommended P dose was reduced (Table 3). Such a shift in application mode might improve the fertilizer use efficiency, consistent with previous reports that the placement of P fertilizer near the crop roots not only reduces P fixation in soil but also significantly improves crop yields (Demisie 2018; De Bauw *et al.* 2021; Ouedraogo *et al.* 2022). Therefore, strip application should also be considered while applying P fertilizers to limit P losses and improve crop yields at the same time.

Moreover, wheat straw was used for wrapping fertilizer in this study. The use of straw with a 20% reduction in P input (SRP_{80} and $SARP_{80}$) showed significant yield performance when compared with the conventional FP and RP. Similarly, the APU, PRR, PFP and AE of the P fertilizer were also significantly improved. One important consideration is that the recovery rate exceeds 100% for most of the treatments,

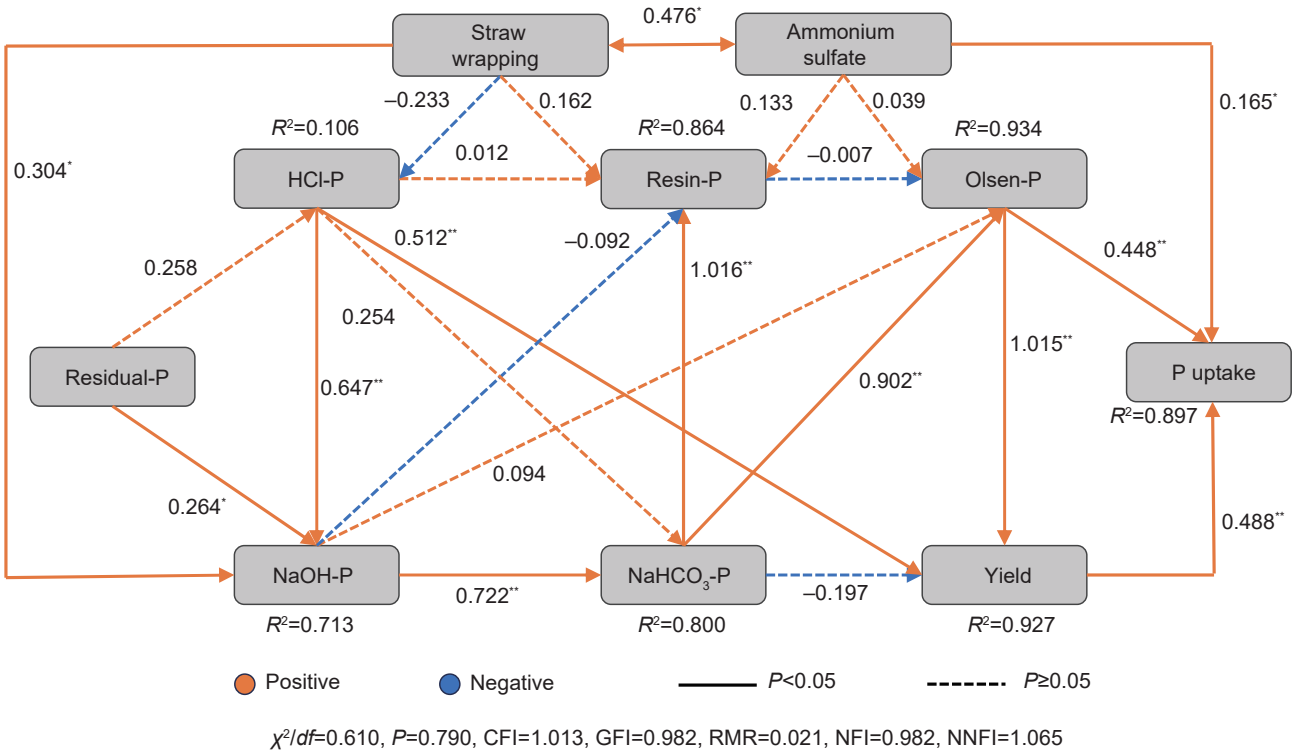


Fig. 6 Structural equation model showing the relationships between different soil P fractions, Olsen-P, crop yield and crop P uptake under the influence of reduced P application with enhancement measures. The orange and blue lines indicate positive and negative relations, respectively. The number above, below or beside each line indicates the standardized path coefficient (*, $P<0.05$, **, $P<0.01$). R^2 is the percentage of variance explained by the predictor. The solid and dotted lines indicate the significant and insignificant paths, respectively.

indicating that the crop might utilize primary soil P, which questions the effectiveness of these application measures in the long run (Table 3). However, the enhancement measures effectively maintained or even enhanced both the total P and Olsen-P over the experimental period (Fig. 2-A) when compared with the baseline values (Table 1). This could be attributed to two factors. First, the decomposition of straw might support the additional supply of P to the labile pool followed by the addition of organic matter to the soil, and this might stimulate the microbial growth that supports the release and transformation of P in the soil. Second, straw wrapping reduces the area of contact between the P fertilizer and the soil, weakens the fixation of soil P, and thus improves the effective utilization of P. These findings are also consistent with those of previous studies. Straw contains different nutrients, and it is known to increase organic matter and available nutrients in the soil, thus supporting crop growth and development (Chen *et al.* 2022a, b). Moreover, another study conducted in suburban Beijing reported that the average annual crop yield was increased by 20% when straw was incorporated into calcareous soil (Wang *et al.* 2022). Therefore, straw-wrapped P fertilizer is an efficient control method for reducing P inputs and improving the efficiency of P in calcareous soils.

In addition, urea was replaced with ammonium sulfate in this study to assess any change in crop yield and P efficiency. The results revealed that even a reduced application of P without straw wrapping (ARP_{80}) significantly improved crop yield as compared to RP_{80}, and the impact was further pronounced when the straw wrapping of P was done along with the application of ammonium sulfate (Fig. 1-A and B). The most probable factor behind this improvement may be the change in pH (Fig. 2-B) near the crop roots, which restricts P fixation in the soil and enhances the availability of P to the crops. The application of ammonium sulfate is known to reduce the soil pH and promote P availability in calcareous soils (Cabral *et al.* 2020; Brownrigg *et al.* 2022). Therefore, ammonium sulfate, instead of urea, is the most effective N source for the wheat–maize rotation system, bearing in mind the sustainable management of P in the calcareous soils. The impact of using acidifying amendments on soil P solubility in calcareous soil was also comprehensively studied in South Australia, and the results revealed that except for soils with relatively high carbonate contents, the amendments increased P solubility (Brownrigg *et al.* 2022), suggesting that ammonium sulfate as an N source is one of the most effective ways to manage P nutrition.

4.2. Distribution of different P fractions and their bio-availability in response to P enhancement measures

The P fractions are complex and generally change in dynamic ways. In this study, the reduction of P fertilizer with enhancement measures showed a profound impact on the labile P (Fig. 3-A–C) and moderately labile P (Fig. 3-D–F) but a non-significant effect on occluded P (Fig. 3-G–I) when compared with the CK. However, in the case of labile inorganic P, FP showed the highest values for $NaHCO_3$-Pi

and Resin-Pi because it received high amounts of inorganic fertilizer while the mineral P input was reduced for successive treatments, resulting in lower contents of labile inorganic P, but it did not influence the crop yield (Fig. 1-A and B). Previous studies reported that $NaHCO_3$-Pi is the most strongly influenced fraction of P in the soil in response to P application (Ciampitti *et al.* 2011; Cheng *et al.* 2020; Biassoni *et al.* 2023).

Similarly, the reduced P dose with straw wrapping and ammonium sulfate instead of urea had profound effects on $NaHCO_3$-Po, NaOH-Po and C.HCl-Po (Fig. 3-C, E and H). The impact of straw return on soil P fractions has been widely studied, and it was found to alter the P fractions in the soil (Gichangi *et al.* 2009; Yang and Lu 2022). This probably happens because straw is a good source of organic matter, soluble P, and certain organic acids, which are released during the decomposition of organic matter, and the organic acids further favors the dissolution of P and reduces its fixation by soil minerals (Zhao *et al.* 2016; Chen *et al.* 2017), thereby enhancing the availability of P to crops and ensuring good yields despite the reduction in recommended P. Second, soil pH has a profound effect on the distribution of different P fractions in response to P fertilizer inputs (Jing *et al.* 2012). In this study, the soil pH was significantly reduced by the treatments that received straw wrapping with ammonium sulfate instead of urea (Fig. 2-B), which might favor the formation of labile ($NaHCO_3$-Po) and moderately labile (NaOH-Po) organic P supporting crop growth despite the P dose reduction by 20%. Previous studies also reported that any change in the soil pH has a profound influence on the distribution of different P fractions in the soil, thereby increasing the availability of soil P (Hinsinger *et al.* 2003; Jing *et al.* 2012; Wang X X *et al.* 2018; Yang *et al.* 2022; Naeem *et al.* 2023).

Moreover, in response to P inputs, the P fractions undergo a significant change with a profound impact on D.HCl-Pi (Wang *et al.* 2020; Wu *et al.* 2021). A similar trend was observed in this experiment. After five consecutive years of reduced P application with enhancement measures, a significant change in the proportions of P fractions was recorded with a major share of D.HCl-Pi (a substantial portion of the moderately labile P) accounting for 70.3–73.7% (Fig. 4-A and B). This suggested that the enhancement measures maintained almost the same levels of D.HCl-Pi under reduced P applications with enhancement measures when compared with the conventional application of high P inputs. This effect was further assessed through correlation analysis (Fig. 5). The results showed that the major portion of moderately labile P (D.HCl-Pi) was positively correlated with Olsen P, suggesting that for the P reduction treatments, the crop P uptake might be mainly supplied by moderately labile P, as previous studies also confirmed that inorganic P is the main agent of change for P availability (Rubio *et al.* 2008; Biassoni *et al.* 2023). Furthermore, the labile and moderately labile inorganic P were positively correlated, suggesting the transformation of moderately labile P into labile P, thereby enhancing the availability of P to the crops for the treatments where P input was reduced with enhancement measures because the occluded P revealed poor correlations with both Olsen P and P uptake, suggesting it is the least influenced fraction of P in response to the enhancement measures. This may reflect the strong interaction of this fraction with soil minerals and organic matter, limiting its transformation into bioavailable forms. For example, the transport, transformation, and bioavailability of P fractions are known to be regulated by the adsorption, desorption, and precipitation of P with different soil components (Sundareshwar *et al.* 2003; Celi and Barberis 2005).

Similarly, the results of the SEM showed multiple transformation paths for soil P, where each P fraction may have a direct or indirect influence (Fig. 6). When P fertilizer is wrapped with straw, the straw might decompose to produce organic matter and stable P, however, it might activate the transformation of occluded P to moderately labile P through the stimulation of microorganisms in the soil. This might somewhat promote the mobility of occluded P to moderately labile or labile P. In contrast, the mobility from moderately labile to labile P might be quite high, which would result in increasing P utilization by crops despite the reduced P application, thereby supporting an optimum crop yield. At the same time, ammonium sulfate reduced the soil pH, which might favor the mobility of P fractions towards labile P. Such similar trends were also found in previous studies (Hinsinger *et al.* 2003; Zhao *et al.* 2016; Chen *et al.* 2017; Naeem *et al.* 2023). Furthermore, D.HCl-Pi alone accounts for about 70% of the overall P fractions. It is relatively stable and not easily leached (Sundareshwar *et al.* 2003; Celi and Barberis 2005; Yang and Post 2011), which might favor its mobility towards labile P over time, resulting in a continuous supply of P to be utilized by the crops.

4.3. Implications and limitations of this study

This study provides a reference for efficiently utilizing accumulated P in the winter wheat–summer maize system on calcareous soils by reducing the continuous supply of high P inputs. The findings of this study can facilitate the formulation of integrated fertility management for enhancing P use efficiency and support both the policymakers and farmers in adopting comprehensive measures not only to minimize P inputs but also to achieve environmental sustainability.

Despite its meaningful contributions to promoting sustainable agricultural practices, this study has certain limitations that should be considered. This study shows that enhancement measures (straw wrapping and ammonium sulfate instead of urea) are useful for improving crop yield and P availability on calcareous soils. However, their effects need to be further verified. Second, sandwiching the fertilizers between two layers of straw may limit the applicability of these enhancement measures on a large scale and may require additional labor costs as compared to the conventional practices. However, based on the findings of this study, future research could focus on formulating straw-based compound P fertilizers that can be easily applied to the soil mechanically, thereby reducing application costs and extending its applicability to large areas. Also, the growing mechanization in the agricultural sector may offer a great opportunity to undertake such practices at a low cost in the

future, even if straw-based fertilizers are not developed.

5. Conclusion

For the winter wheat–summer maize crop system in the Guanzhong Plain, reducing the current conventional P fertilizer application rate of 180 to 120 kg P_2O_5 ha^{-1} (recommended dose) can guarantee an optimum crop yield. Furthermore, a 20% reduction based on the recommended P input can be achieved without compromising crop development if the effectiveness of soil P components is increased through straw wrapping and ammonium sulfate instead of urea. Therefore, these enhancement measures can be a promising way to reduce P input in calcareous soils to prevent both its loss and the environmental concerns associated with the non-judicious use of P fertilizer.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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