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The Impact of Different Phosphorus Fertilizers Varieties on Yield under Wheat–Maize Rotation Conditions

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Abstract: The global phosphate (P) rock shortage has become a significant challenge. Furthermore, the misalignment between crops, soil, and P usage exacerbates P rock wastage in agriculture. The distinctions among various types of phosphorus fertilizers influence the phosphorus cycle, which subsequently impacts biomass, the number of grains per ear, the weight of a thousand grains, and, ultimately, the overall yield. In a four-year field experiment conducted from 2017 to 2021, we assessed the impact of various P fertilizer types on crop yield in a continuous wheat–maize rotation system. Prior to planting the crops, P fertilizers were applied as base fertilizers at a rate of 115 kg P_2O_5 ha^{-1} during the wheat season and 90 kg P_2O_5 ha^{-1} during the maize season. Additionally, nitrogen (N) was applied at rates of 120 kg ha^{-1} for wheat and 180 kg ha^{-1} for maize. The P fertilizers used included ammonium dihydrogen phosphate, ammonium polyphosphate, calcium–magnesia phosphate, ammonium phosphate, and calcium superphosphate. Urea was used as the N fertilizer with a split application—60% at planting and 40% at the jointing stage for wheat or the V12 (twelve leaf collar) stage for maize. The results showed that different P fertilizers increased the average yield of wheat and maize by 21.2–38.0% and 9.9–16.3%, respectively. It was found that ammonium polyphosphate, calcium superphosphate, and monoammonium phosphate were more suitable for application in a summer maize–winter wheat rotation system on loess soil.

Keywords: alkaline soil; crop yields; loess plateau; yield components; phosphorus uptake

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1. Introduction

In recent decades, the global agricultural use of phosphate (P) fertilizer has seen a significant increase, rising from 4.6 million tons in 1961 to around 21 million tons in 2015 [1,2]. Phosphate rock (PR) serves as the primary source of P fertilizer, but it is a non-renewable resource [3]. The extensive application of P on farmland is a major factor contributing to the shortage of PR, with almost 90% of PR being utilized for P fertilizer production [3,4]. Addressing the sustainability of PR resources necessitates the adoption of appropriate and sustainable P application practices.

With the development of industrial levels and in-depth research, some phosphorus-containing compounds have been found to better maintain the available phosphorus content in the soil, and are therefore gradually being applied to agricultural production as fertilizers, including monoammonium phosphate, diammonium phosphate, calcium–magnesium phosphate, ammonium polyphosphate, and calcium superphosphate [5]. In China, the application of P fertilizer to farmland is often inefficient, as many farmers lack

access to professional guidance within the prevalent self-employed farming model [6–8]. The prevalent mismatch between P fertilizer types, crops, and soil contributes to significant wastage of P fertilizers and poses risks to soil and water quality [9–12]. The unsustainable use of P could deplete PR reserves within a few centuries unless appropriate practices are adopted [2,13]. Optimizing the use of phosphate fertilizer is of great significance for the sustainable development of regional agriculture.

While many studies have assessed the impact of P fertilizer quantities on crops, there is limited research on the effects of different P fertilizer types on crop yields [9,14–16]. Furthermore, studies have examined the effects of P fertilizers on crops and soils in various scenarios, such as with the addition of biochar [17], straw [18,19], humic acid [20,21], or the partial replacement of inorganic P with organic manure [22,23]. In the process of the soil plant phosphorus cycle, nitrogen often plays a huge role, and there is a wide range of nitrogen and phosphorus synergy in nature, so we also need to pay attention to the impact of phosphorus fertilizer differences on nitrogen use efficiency.

At the same time, the importance of selecting appropriate P fertilizer varieties for enhancing the industrial structure of P fertilizer is often overlooked [24]. During the growth process of crops, biomass is continuously accumulated and gradually differentiated into various organs. Therefore, the difference of phosphorus supply will be shown in the development of different organs. For example, phosphorus deficiency at the flowering stage may lead to fewer grains per ear, and phosphorus deficiency at the filling stage may lead to lower 1000-grain weight. The study of yield components is helpful to understand the absorption and utilization of elements in different growth stages.

There are extensive calcareous soils in China, which are characterized by high pH and rich carbonate content. It is generally believed that under the action of higher pH, free carbonate can combine with phosphorus to form insoluble phosphate, which reduces the concentration and mobility of phosphorus in soil solution, resulting in phosphorus becoming a limiting factor for crop growth [25].

Wheat and maize play vital roles in China's food security, being key components of the three major food crops. The winter wheat–summer maize rotation system is the predominant crop planting pattern in northern China [26,27]. The Loess Plateau is located in the semi-arid region of China. The soil's phosphorus content is low, the soil is alkaline [28], the demand for phosphorus fertilizer is large, and the main food crops are wheat and maize.

Therefore, in this study, we conducted a four-year field experiment to assess the effects of various P fertilizer types on crops in a continuous wheat–maize rotation from 2017 to 2021. The aims of the study were to find what kind of phosphorus fertilizer is more suitable for maize and wheat production in alkaline soil, to explain why these phosphorus fertilizers are more suitable for the growth of maize and wheat, and to provide better guidance for grain production in the Loess Plateau.

2. Materials and Methods

From October 2017 to September 2021, a four-year field experiment was conducted to investigate the effects of different phosphorus fertilizers on the wheat–maize rotation system. The experiment was conducted at the Experimental Station of the Northwest Agricultural and Forestry University in Yangling, Shaanxi, China. The experimental site is located at 34°17′44″ N, 108°04′10″ E, altitude 520.3 m. The experiment was conducted in the southern part of the Loess Plateau (Figure 1).

The soil type was classified as eroded illuvial clay soil (Haplic Luvisols), according to the World Reference Base for Soil Resources WRB (IUSS Working Group WRB 2022). The properties of the soil (0–20 cm soil layer) are shown in Table 1 (September 2017). The meteorological data during the experiment is shown in Figure 2. During the experiment, typical rain and heat synchronization was observed. The annual rainfall ranges from 711.1 mm to 780.2 mm.

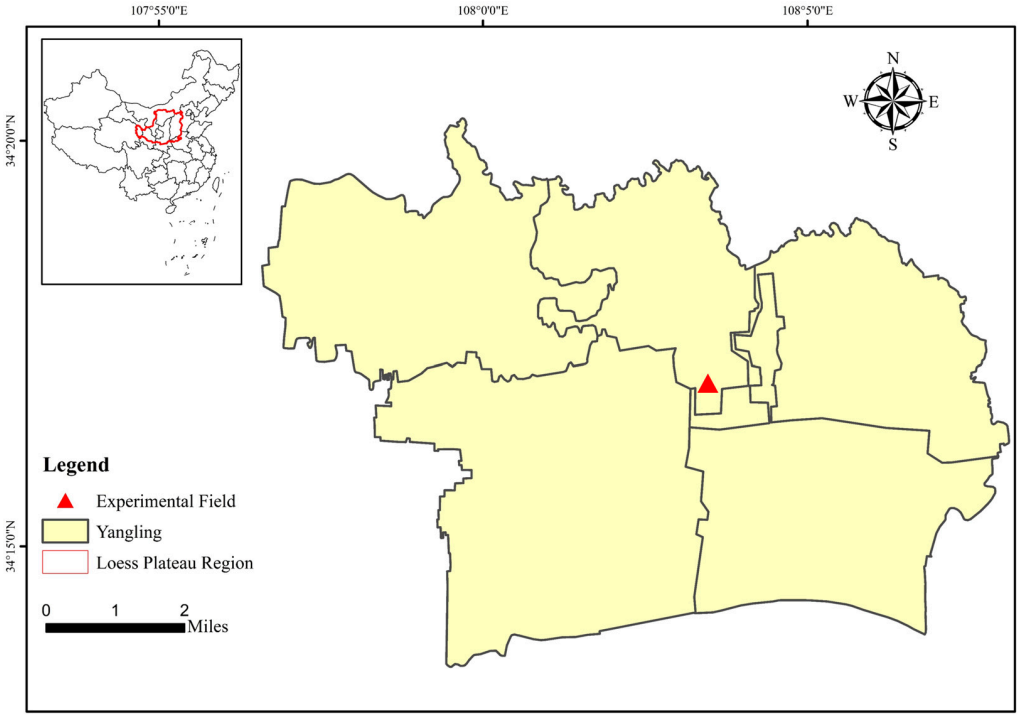


Figure 1. Location of the study area.

Table 1. Soil properties before the start of the experiment.

pH (Soil:Water 1:2.5)	Organic Carbon (OC) ($g \cdot kg^{-1}$)	Total Nitrogen (TN) ($g \cdot kg^{-1}$)	Total Phosphorus (TP) ($g \cdot kg^{-1}$)	$CaCO_3$ ($g \cdot kg^{-1}$)	Available Phosphorous (AP) ($mg \cdot kg^{-1}$)	Available Potassium (AK) ($mg \cdot kg^{-1}$)	The Percentage of Sand %	The Percentage of Silt %	The Percentage of Clay %
8.21	10.5	0.92	0.84	59.7	20.7	148.6	2.9	71.42	25.68

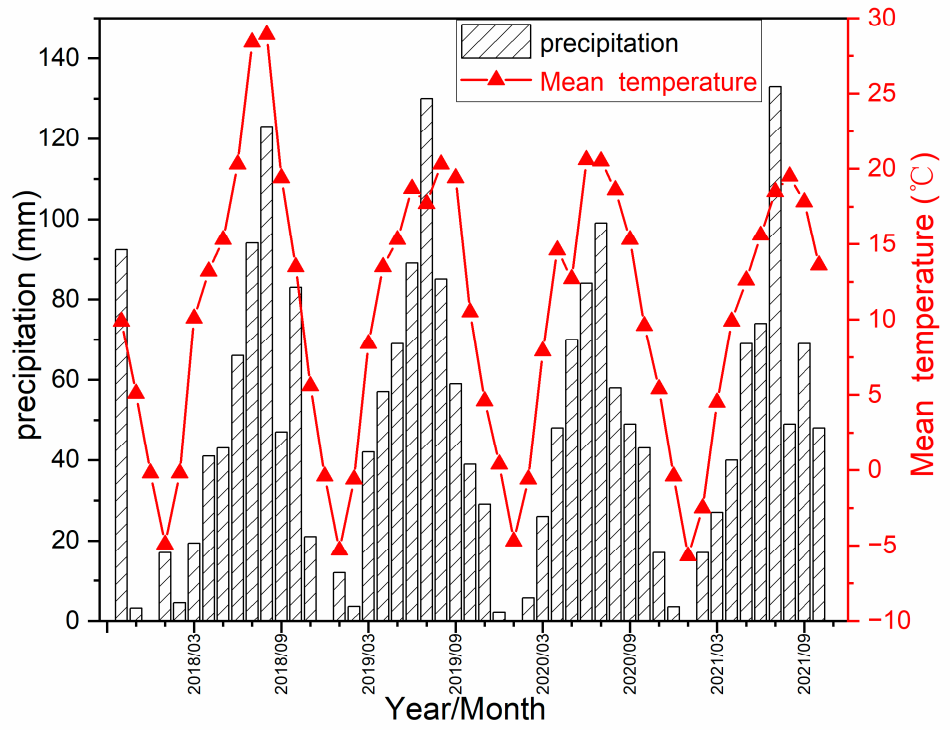


Figure 2. Distribution of the precipitation and temperature at Yangling from 2017 to 2021.

2.1. Experimental Design

The study implemented a four-cycle rotation of winter wheat and summer maize. Winter wheat was sown in mid-October and harvested in early June of the subsequent year, while summer maize was planted in mid-June and harvested in early October. Experimental plots—each measurement was conducted in an area of 3.5 m × 4 m (14 m^2)—were arranged in a randomized block design with four replicates (Figure 3). Planting densities were maintained at 180 kg ha^{-1} of seeds for wheat and 25 kg ha^{-1} for maize. The wheat and maize varieties were "xiaoyan 22" and "zhengdan 958", respectively.

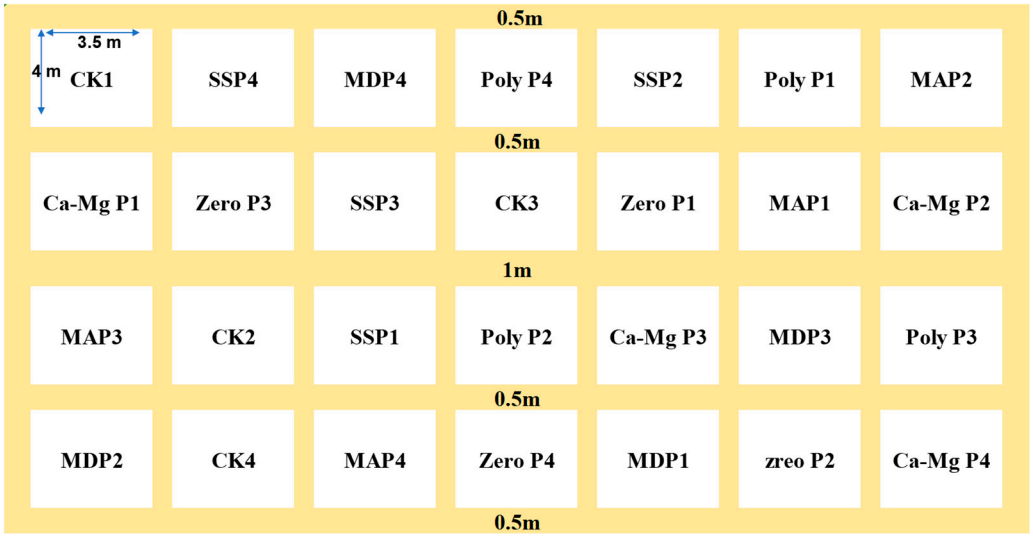


Figure 3. Experimental distribution diagram.

Prior to planting, foundational fertilizers were evenly spread across the experimental plots, followed by uniform plowing using a rotary tiller. Subsequently, seeds were planted with a row spacing of 25 cm for wheat and 55 cm for maize using a seeder. Throughout the experimental duration, no irrigation was applied, and standardized plot management practices were maintained consistently.

The study comprised seven treatments with four replicates each: a control group without any fertilizer (CK); a treatment with only nitrogen and no phosphorus fertilizer (Zero P); and five phosphorus fertilizer treatments: ammonium dihydrogen phosphate (MAP), diammonium phosphate (DAP), calcium–magnesia phosphate (Ca-Mg P), calcium superphosphate (SSP), and ammonium polyphosphate (Poly P). Phosphorus fertilizer was applied once as basal fertilizer at rates of 115 kg P_2O_5 ha^{-1} and 90 kg P_2O_5 ha^{-1} during the wheat and maize season, respectively (Table 2). The nitrogen application rate as basal fertilizer for wheat was 72 kg N ha^{-1}, and for maize, it was 108 kg N ha^{-1}. Nitrogen was then applied at a rate of 48 kg N ha^{-1} at the wheat jointing stage and 72 kg N ha^{-1} at the maize V12 stage. In accordance with the local management program, no potassium fertilizer was used in any treatment.

Table 2. Properties and application amounts of different phosphate fertilizers.

P Fertilizers	Acid-Base Properties	Solubility	P_2O_5 (%)	P Fertilizer (kg ha^{-1})-Wheat Season	P Fertilizer (kg ha^{-1})-Maize Season
SSP	Alkaline	Water-soluble	45	255.56	200
AP	Alkaline	Water-soluble	60.5	190.08	148.76
DAP	Acidic	Water-soluble	53.8	213.75	167.26
Poly P	neutral	Water-soluble	58	198.27	155.17
Ca-Mg P	Alkaline	Weakly acid soluble	18	638.89	500

2.2. Sample Collection and Determination

Soil samples were meticulously collected using a drill, both prior to the experiment's initiation and post-harvest of either wheat or maize. Samples were extracted from the surface layer (0–20 cm) at five distinct locations within each plot, adhering to an S-shaped route, and subsequently amalgamated to form composite samples. The freshly obtained soil samples underwent thorough mixing, followed by air-drying and sieving through a 2.0 mm screen, before being securely stored in sealed plastic jars for subsequent analysis.

The determination of total phosphorus (P) and Olsen-P content was conducted employing the ammonium molybdate method, as elucidated by Murphy and Riley [29]. Furthermore, soil total nitrogen (N) content was assessed utilizing the Kjeldahl method, following the protocol outlined by Kirk [30].

Upon reaching maturity, crops from a designated 4 m^2 area at the center of each plot were meticulously collected to assess yield for each treatment. Subsequently, the residual plants were harvested by close-ground cutting and, after collection, underwent drying. An estimation of aboveground biomass was then carried out. Plant samples were pulverized to pass through a 0.5 mm sieve and subjected to digestion using concentrated sulfuric acid/hydrogen peroxide, as described by Li [31]. This process facilitated the measurement of phosphorus and nitrogen content for plants across various growth stages. All reagents are produced by China National Pharmaceutical Group (Beijing, China).

2.3. Data Calculation and Analysis

Data analysis included calculating the recovery efficiency of phosphorus (RE_P) [32], the agronomic efficiency of phosphorus (AE_P), ref. [33], and the partial factor productivity from applied phosphorus (PFP_P) [34] using established formulas.

$$RE_p = \frac{(U_p - U_0)}{F_p}$$

where Up and U_0 are aboveground crop P uptake in P treatment plots and Zero P treatment plots, respectively. Fp is the amount of the applied P fertilizer.

$$AE_p = \frac{(Y_p - Y_0)}{F_p}$$

$$PFP_p = \frac{Y_p}{F_p}$$

where Yp and Y_0 are grain yield of application P treatment plots and Zero P treatment plots, respectively. Fp is the amount of the applied P fertilizer.

The above calculations are based on the annual average.

Statistical analysis was performed using IBM SPSS statistics 24, and correlations between variables were analyzed using R 3.6.3, and principal component analysis (PCA) was conducted using Canoco 5 [35].

3. Results

3.1. Crop Yields and Biomass Accumulation

The yields of wheat and maize were consistently lowest in the control group (CK) throughout the four-year study period. Notably, yields in the CK group exhibited a decreasing trend over the years. While the Zero P treatment showed higher yields compared to CK, it also displayed a declining trend annually, confirming previous findings indicating the limiting effect of phosphorus (P) fertilizers on crop yields (Table 3) [13,36].

Different varieties of P fertilizers exerted varied effects on crop yields. Poly P, MAP, and SSP were more effective in promoting wheat and maize growth on the Loess Plateau compared to Ca-Mg P and DAP. The yields in P fertilizer treatments were notably higher than CK, with increases ranging from 43.3% to 63.2% for wheat and from 27.6% to 35.0%

for maize. Additionally, compared to the Zero P treatment, P treatments increased wheat yields by 21.2–38.0% and maize yields by 9.9–16.3% (Table 3).

Table 3. Grain yields of wheat and maize from different treatments during 2017–2021.

Wheat Grain Yield (kg ha^{-1})							
Treatment	CK	Zero P	Poly P	MAP	Ca-Mg P	SSP	DAP
2017–2018	5537 d [1]	6249 c	7995 a	7913 a	6933 b	7811 a	6967 b
2018–2019	5081 e	5956 d	8029 ab	8164 a	7079 c	7840 b	7111 c
2019–2020	4840 d	5745 c	8067 a	8017 a	7189 b	7898 a	7135 b
2020–2021	4296 e	5415 d	8158 a	8097 ab	7110 c	7901 b	7118 c
Mean yield (kg·ha^{-1})	4939	5841	8062	8048	7078	7863	7083
Change to CK (%)	0	18.3	63.2	62.9	43.3	59.2	43.4
Change to Zero P (%)	−18.3	0	38	37.8	21.2	34.6	21.2
Maize Grain Yield (kg ha^{-1})							
Treatment	CK	Zero P	Poly P	MAP	Ca-Mg P	SSP	DAP
2018	5045 e	5840 d	6295 b	6382 ab	6052 c	6458 a	6088 c
2019	4825 d	5678 c	6311 a	6368 a	6081 b	6230 a	5998 b
2020	4665 d	5482 c	6459 a	6398 a	6005 b	6277 ab	6040 b
2021	4431 e	5028 d	6548 a	6432 a	6071 c	6269 b	6099 c
Mean yield (kg·ha^{-1})	4742	5507	6403	6395	6052	6309	6056
Change to CK (%)	0	16.1	35	34.9	27.6	33	27.7
Change to Zero P (%)	−16.1	0	16.3	16.1	9.9	14.6	10

[1] Means followed by similar letters in each row are not significantly different ($p > 0.05$), as analyzed by one-way ANOVA and Duncan's multiple range test. CK: No fertilizer control; Zero phosphorus: Only nitrogen fertilizer is applied, no phosphate fertilizer; Poly P: Ammonium polyphosphate; MAP: Ammonium dihydrogen phosphate fertilizer; Calcium–magnesium phosphate fertilizer: Calcium–magnesium phosphate fertilizer; SSP: Superphosphate; DAP: diammonium phosphate fertilizer. The same below.

Aboveground biomass was lowest in CK for both wheat and maize throughout the study period. Although there was no significant difference in aboveground biomass among different P treatments during the wheat growing seasons, all P treatments exhibited significantly higher biomass compared to CK and Zero P. Notably, Poly P and MAP treatments consistently showed higher aboveground biomass than DAP, SSP, and Ca-Mg P during wheat growing seasons (Figure 4A,D). The aboveground biomass of CK and Zero P showed a significant downward trend, as crop growth consumed soil nutrients, exacerbating the deficiency of phosphorus fertilizer (Figure 4A,D).

3.2. Grain Yield Components

The Poly P treatment consistently exhibited the highest grains per spike during the wheat seasons over the four years (Table 4). While the MAP treatment initially showed low wheat grains per spike in 2017, it demonstrated higher values in subsequent years (Figure 4B). In general, wheat grains per spike in P fertilizer treatments were significantly higher than in CK and Zero P. However, during maize seasons, there were no significant differences between MAP, DAP, Poly P, SSP, Ca-Mg P, and Zero P (Figure 4E).

Table 4. The average aboveground biomass, grains per spike/ear, 1000-grain weight at wheat and maize harvest under different P treatment.

		Year	CK	Zore P	Poly P	MAP	MDP	SSP	Ca-Mg P
wheat	aboveground biomass (kg ha^{-1})	2017–2018	11,237.00 Ae	14,474.00 Ad	16,598.33 Aab	16,346.00 Ac	16,201.00 Ac	16,372.00 Abc	16,064.33 Ac
		2018–2019	10,192.67 Ac	13,974.00 Ab	16,553.33 Aa	16,517.33 Aa	16,236.00 Aa	16,382.67 Aa	16,153.33 Aab
		2019–2020	9936.33 Bd	13,293.33 Bc	16,829.33 Aa	16,870.33 Aa	16,356.00 Ab	16,397.33 Ab	16,273.00 Ab
		2020–2021	9714.67 Ce	11,654.33 Cd	17,109.00 Aa	16,926.67 Ab	16,372.00 Ac	16,448.00 Ac	16,273.33 AAc
	grains per spike	2017–2018	21.67 Ac	26.33 Ab	33.33 Aa	34.33 Aa	35.33 Aa	37.00 Aa	33.33 Aa
		2018–2019	20.33 Ae	25.00 Ad	33.67 Ac	37.33 Aa	36.67 Aab	37.00 Aa	35.00 Abc
		2019–2020	18.33 Bc	23.67 Bb	38.00 Aa	38.33 Aa	37.33 Aa	37.67 Aa	36.00 Aa
		2020–2021	17.67 Bd	22.67 Bc	40.00 Aa	38.67 Ab	38.00 Ab	38.67 Ab	37.00 Ab

Table 4. *Cont.*

		Year	CK	Zore P	Poly P	MAP	MDP	SSP	Ca-Mg P
wheat	1000-grain weight (g)	2017–2018	22.00 Ae	26.00 Ad	38.00 Ca	37.67 Ba	35.33 Ab	38.67 Aa	32.67 Cc
		2018–2019	20.33 Ad	23.67 Ac	37.67 Cb	36.00 Bb	35.33 Ab	39.33 Aa	35.67 BCb
		2019–2020	18.33 Bd	22.00 Bc	41.00 Ba	39.67 Ab	38.00 Ab	38.67 Ab	37.00 Bb
		2020–2021	18.67 Be	19.67 Cd	43.00 Aa	40.33 Ab	39.67 Abc	39.33 Abc	38.67 Ac
maize	aboveground biomass (kg ha^{-1})	2018	7110.00 Ae	9024.33 Ad	14,645.00 Ac	150,00.00 Ab	16,416.33 Aa	15,314.67 Ab	14,536.00 Bc
		2019	6933.67 Ae	8902.00 Bd	15,132.33 Abc	154,91.33 Ab	16,157.00 Aa	14,883.33 Bc	15,039.00 Abc
		2020	6560.67 Ad	8616.33 Bc	16,104.00 Aa	156,13.33 Ab	15,369.67 Ab	15,225.67 Ab	15,345.67 Ab
		2021	6281.33 Ad	8077.00 Cc	16,283.67 Aa	161,53.00 Aa	15,356.33 Ab	15,254.33 Ab	15,239.00 Ab
	grains per spike	2018	403.00 Ab	466.33 Aa	475.33 Aa	449.00 Aa	446.33 Aa	471.33 Aa	451.67 Aa
		2019	402.33 Ad	450.33 Ac	486.00 Aa	468.33 Ab	454.00 Ac	460.67 Ab	461.33 Ab
		2020	397.33 Be	442.33 Bd	485.00 Aa	469.00 Ab	467.00 Ab	455.33 Ac	470.33 Ab
		2021	385.33 Cd	433.33 ABc	463.00 Aa	455.33 Ab	468.00 Aa	445.67 Ab	452.33 Ab
	1000-grain weight (g)	2018	215.67 Ad	256.33 Ac	277.67 Ab	294.00 Aa	270.67 Ab	280.67 Ab	259.00 Ac
		2019	199.33 Ae	250.67 Ad	270.67 Ac	305.00 Aa	283.67 Ab	295.67 Aa	284.33 Ab
		2020	196.67 Ad	234.33 Ac	266.67 Ab	293.00 Aa	270.33 Ab	269.00 Ab	279.67 Ab
		2021	192.00 Ae	242.00 Ad	260.67 Ac	286.00 Aab	265.33 Ac	295.33 Aa	278.00 Ab

Note: different uppercase letters represent the significant difference between different years; different lowercase letters represent significant differences between treatments ($p < 0.05$).

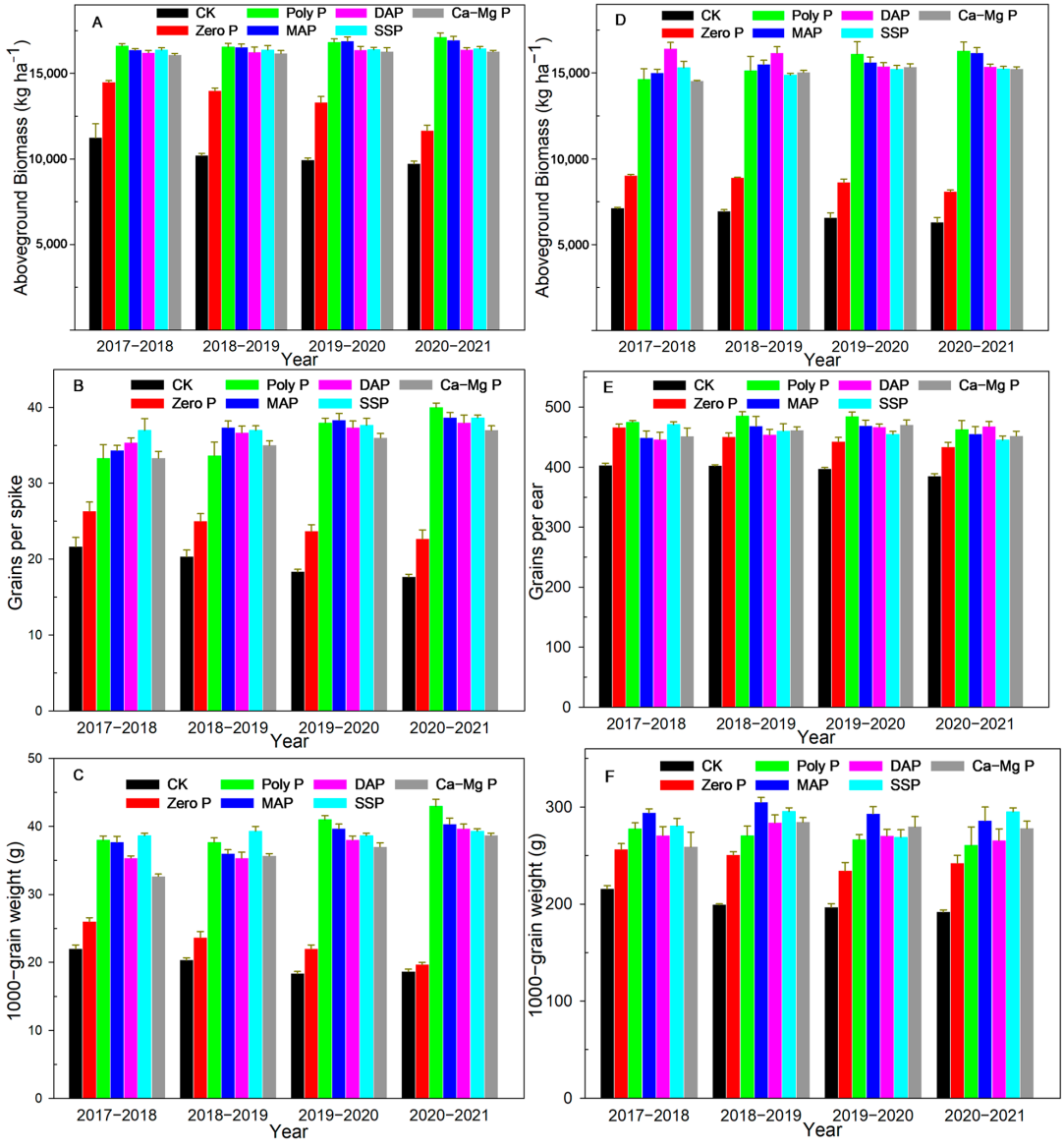


Figure 4. Aboveground biomass, grains per spike/ear, 1000-grain weight at wheat and maize harvest under different P treatments. (**A**–**C**) stands for wheat, (**D**–**F**) stands for maize.

The 1000-grain weights of both wheat and maize were significantly affected by P fertilizer varieties, with P treatments significantly increasing weights compared to CK and Zero P. Notably, Poly P treatment consistently exhibited the highest 1000-grain weights among P treatments, particularly in 2021 (Figure 4C,F).

3.3. Plant N and P Uptake in Wheat and Maize

Over four years, different P fertilizer varieties not only affected P uptake but also influenced N uptake by wheat and maize. P fertilizers significantly increased N uptake by wheat and maize. After the jointing stage of wheat, Poly P and MAP treatments showed significantly higher P uptake compared to DAP, SSP, and Ca-Mg P treatments. Similarly, the average N and P uptake by wheat among Poly P, SSP, and MAP treatments were significantly higher than DAP and Ca-Mg P treatments at the mature stage. Overall, Poly P, SSP, and MAP treatments were more beneficial for wheat and maize growth on the Loess Plateau (Figure 5).

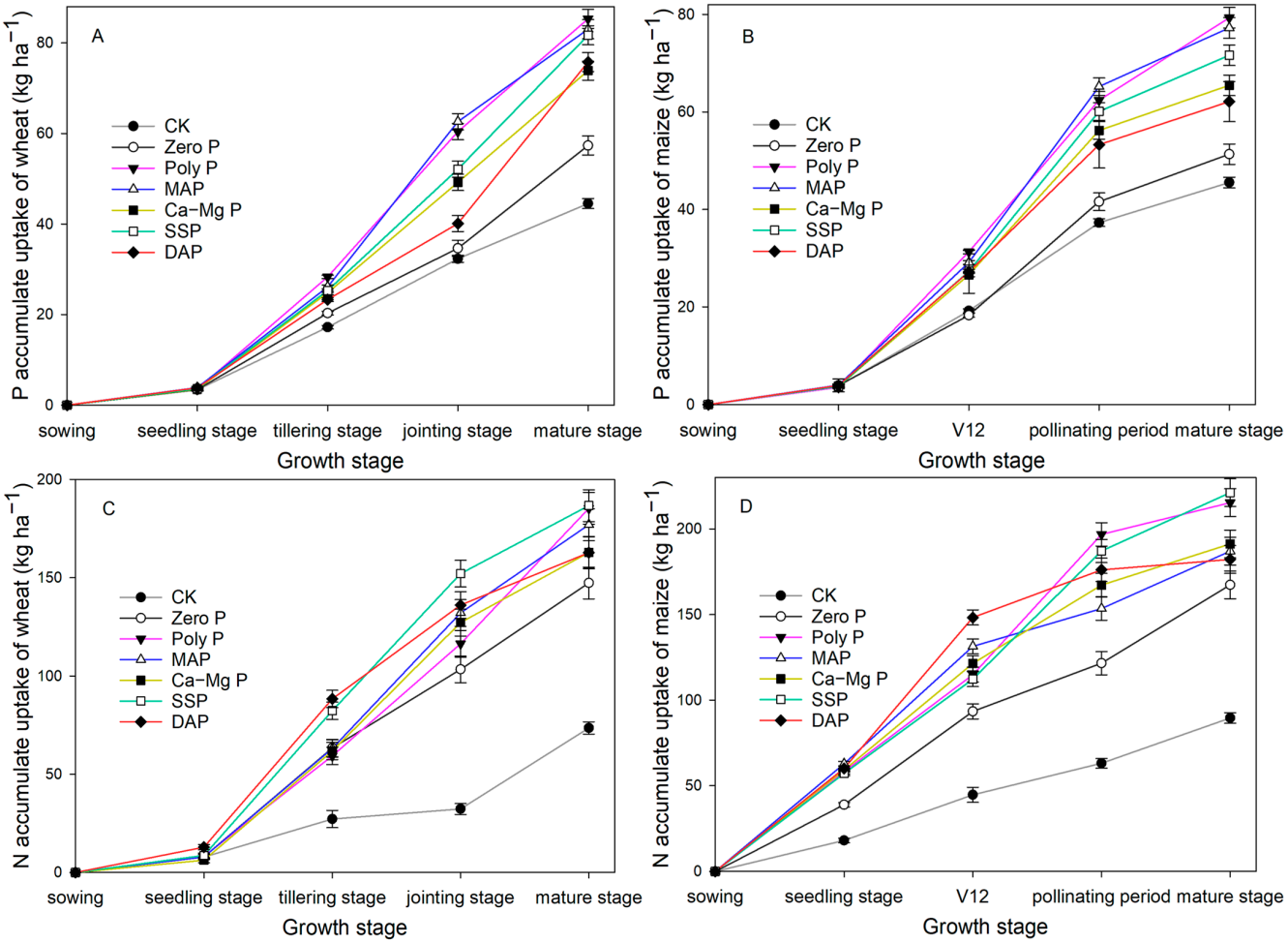


Figure 5. Average plant N and P accumulation uptake at different stages of growth over four years. The graph (**A**–**D**) shows the four-year average value.

3.4. Phosphorus and Nitrogen Efficiency

The plant uptake of N and P were measured, respectively, to assess RE_N and RE_P after the crops were harvested. RE, AE, and PFP were all measured to better comprehend the efficiency of N and P.

RE_P, AE_P, and PFP_P were affected by P fertilizer varieties. The RE_P of Poly P, MAP, and SSP were significantly higher than those of Ca-Mg P and DAP. The highest and lowest RE_P were observed in MAP and Ca-Mg P treatment, respectively, in wheat season.

The PFP_P of the five P fertilizer varieties were from 61.55 kg kg^{-1} to 70.1 kg kg^{-1} in wheat season and from 67.29 kg kg^{-1} to 71.14 kg kg^{-1} in maize season. There was no significant difference in PFP_P between Poly P, MAP, and SSP in maize and wheat seasons. The PFPP in the wheat season was slightly higher than that in the maize season, and the highest PFPP was from Poly P processing (Table 5).

Table 5. Recovery efficiency (RE), partial factor productivity (PFP), and agronomic efficiency (AE) of P and of N.

Treatment	Wheat					
	RE_P	PFP_P	AE_P	RE_N	PFP_N	AE_N
Zero P	-	-	-	26.11 c	48.68 c	7.52 c
Poly P	36.49 a [1]	70.1 a	19.31 a	34.20 a	67.18 a	26.03 a
MAP	37.12 a	69.98 a	19.19 a	34.95 a	67.07 a	25.91 a
Ca-Mg P	33.51 b	61.55 b	10.76 c	30.82 b	58.98 b	17.83 b
SSP	36.83 a	68.37 a	17.58 b	33.65 a	65.53 a	24.37 a
DAP	33.71 b	61.59 b	10.8 c	31.44 b	59.03 b	17.87 b
	Maize					
	RE_P	PFP_P	AE_P	RE_N	PFP_N	AE_N
Zero P	-	-	-	26.26 d	30.59 c	4.25 d
Poly P	35.42 a	71.14 a	9.96 a	36.18 a	35.57 a	9.23 a
MAP	35.37 a	71.06 a	9.87 a	35.96 a	35.53 a	9.18 a
Ca-Mg P	34.08 a	67.24 b	6.06 c	31.99 c	33.62 b	7.28 c
SSP	35.42 a	70.1 a	8.91 b	36.28 a	35.05 a	8.71 ab
DAP	33.99 b	67.29 b	6.1 c	33.75 b	33.64 b	7.3 bc

[1] Means followed by similar letter within each column were not significantly different ($p > 0.05$) based on analyses by one-way ANOVAs followed by Duncan's multiple range test. RE_P (%): recovery efficiency of phosphorus; PFP_P (kg kg^{-1}): partial factor productivity from applied phosphorus; AE_P (kg kg^{-1}): agronomic efficiency of phosphorus; RE_N (%): recovery efficiency of nitrogen; PFP_N (kg kg^{-1}): partial factor productivity from applied nitrogen; AE_N (kg kg^{-1}): agronomic efficiency of nitrogen.

The AE_P of the five P fertilizers were, in order, Poly P > MAP > SSP > DAP > Ca-Mg P in wheat and maize season. There was no significant difference in AEP between Poly P, MAP, and SSP in wheat season. However, the AEP of SPP treatment was significantly lower than that of Poly P and MAP.

The intervention of P fertilizer can effectively increase the absorption of N by crops. The RE_N of Poly P, MAP, Ca-Mg P, SSP, and DAP treatment increased by 30.98%, 33.86%, 17.81%, 28.88%, and 20.41%, respectively, compared to Zero P treatment in wheat season. And the corresponding increases were 37.78%, 36.94%, 21.82%, 38.16%, and 28.52%, respectively, compared with that of Zero P treatment in maize season. P fertilizer also significantly affects the AE_N and PFP_N.

3.5. Soil Olsen-P and TP

Olsen-P and TP were all consumed for CK and Zero P treatment due to the plants taking away part of the soil P. The Olsen-P and TP content of P fertilizers treatment were higher than the Zero P and CK after the crops were harvested each year (Figure 6). During the wheat season, the TP of MAP treatment was the highest, and there is little difference in the TP content between DAP, SSP, Poly P, and Ca-Mg P (Figure 6A). There is no strong regularity of TP content in the maize season, except that the TP content of CK and Zero P showed a decreasing trend year by year (Figure 6C).

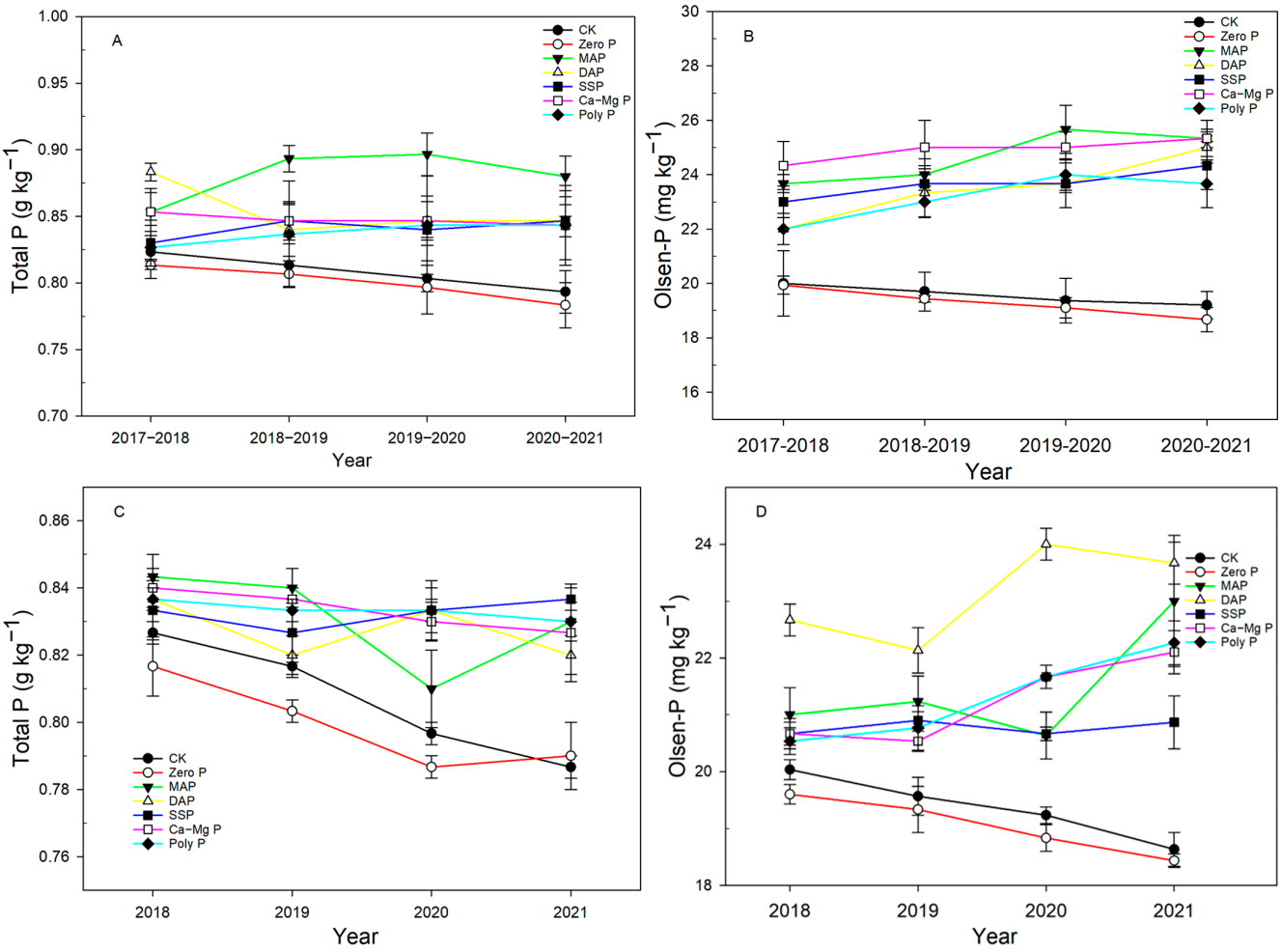


Figure 6. Harvest-season soil phosphorus content. (**A**,**B**) is the total P and Olsen-P content during the wheat harvest season. (**C**,**D**) is the total P and Olsen-P content during the maize harvest season.

3.6. Relationships among Soil Properties, Plant Accumulation P Uptake (PPU), Plant Accumulation N Uptake (PNU), Growth Indicators, and Yield Components

The correlations among soil properties, wheat growth indicators, plant uptake of nutrients, and yield components was analyzed (Figure 7). Highly significant correlations were found between GY, TGW, GPS, and AB for winter wheat during the four years of the study. However, the relationship between wheat yield and soil nutrient content after crop harvest was not significant. Both PPU and PNU showed a close correlation in wheat and maize season (Figure 7A). The GY of wheat and maize was significantly affected by PUP and PUN.

3.7. Principal Component Analysis

Principal component analysis highlighted the close relationship between P fertilizers and growth indices (Figure 8). There was a significant difference between the treatment using phosphorus fertilizer and the treatment not using phosphorus fertilizer. Zero P and CK also showed significant differences. In wheat, PC1 is 91.5%, and in maize, PC1 is 77.6%. GY has a better correlation with PPU. There is a poor correlation between AP and GY.

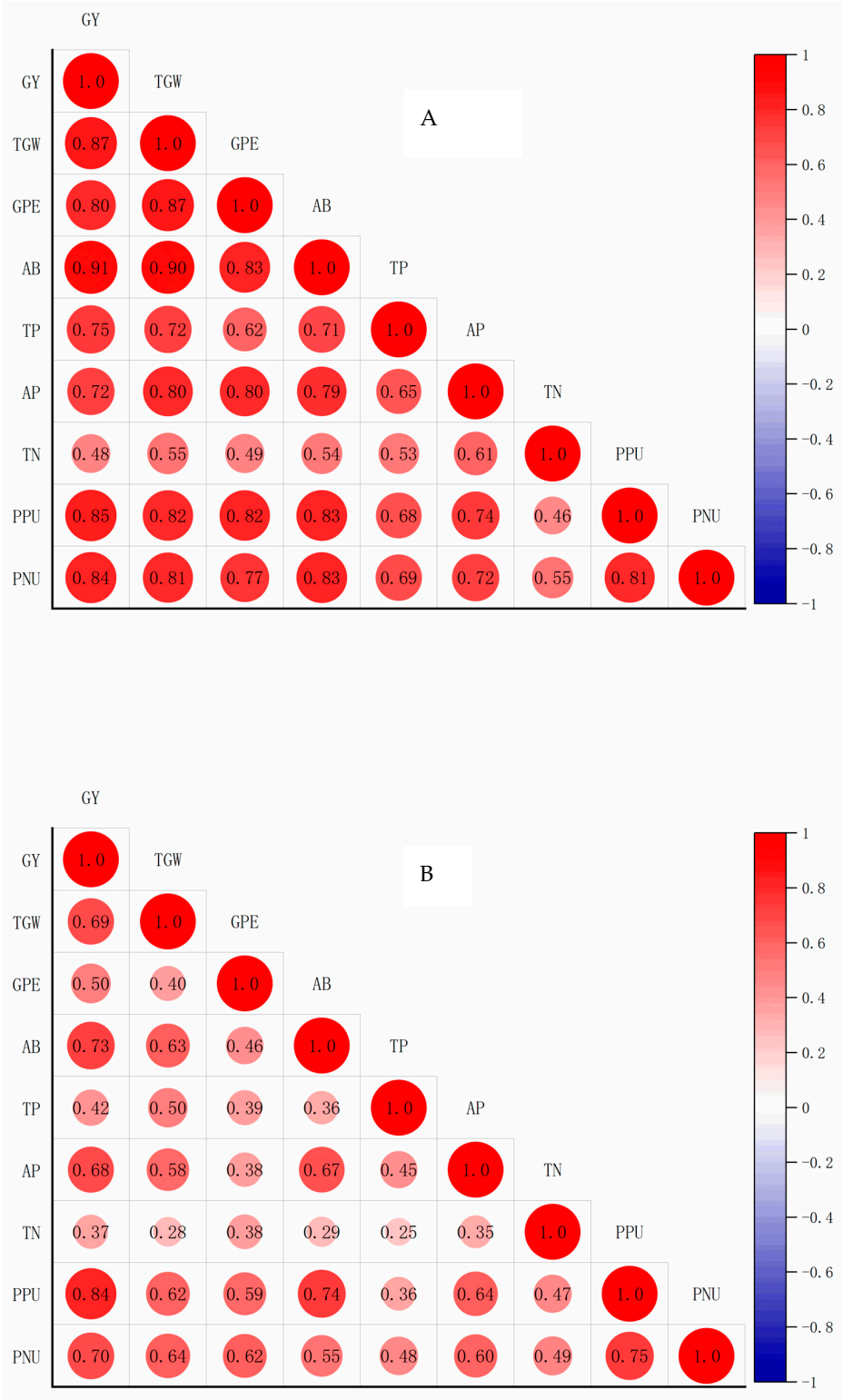


Figure 7. Correlations among soil properties, yield components, and plant N/P uptake from 2017 to 2021. (**A**): winter wheat growing season, (**B**): summer maize growing season. GY, grain yield (kg ha^{-1}); TGW, 1000-grain weight (g); GPE/S, grains per spike/ear; AB, aboveground biomass (kg ha^{-1}); TP, total phosphorus (g kg^{-1}); AP, available phosphorus (mg kg^{-1}); TN, total nitrogen (g kg^{-1}); PPU, plant accumulation P uptake (kg ha^{-1}); PNU, plant accumulation N uptake (kg ha^{-1}).

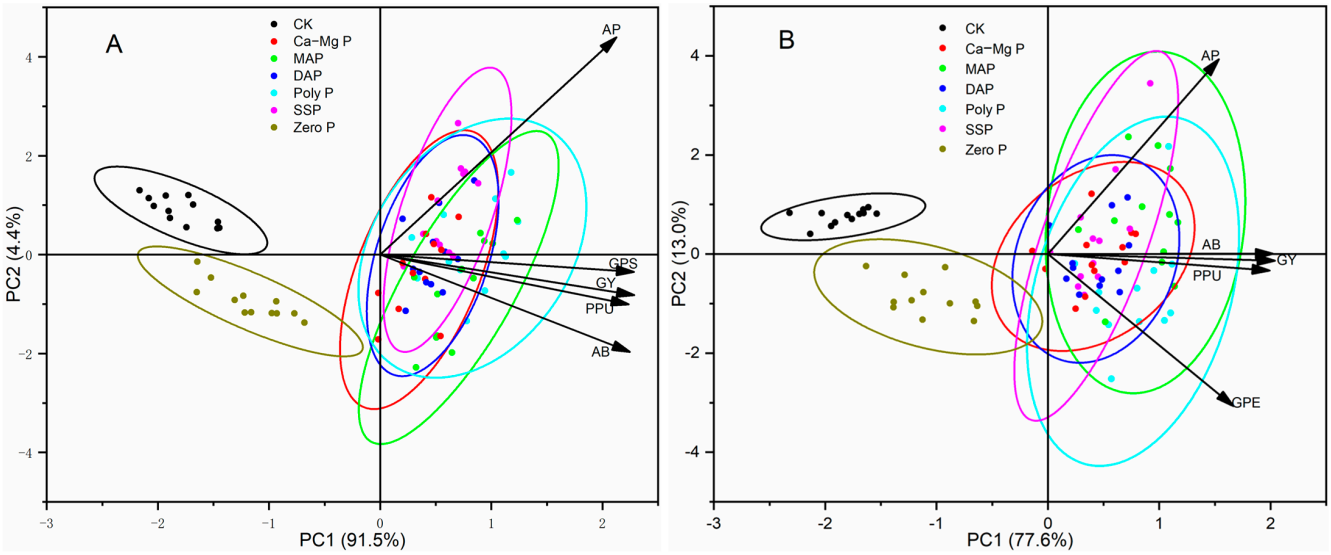


Figure 8. PCA of the relationship between the P fertilizer varieties and growth indicators. (**A**) wheat; (**B**) maize.

4. Discussion

4.1. Effects of Different P Fertilizer Varieties on Crop Growth and Yield

As early as the 1970s, it was confirmed that soil type can affect plant mineral composition [37]. In addition, phosphorus sources have significant effects on the production of crops [38]. Calcareous soil will absorb and form a large amount of phosphate, which is insoluble in water, leading to the reduction of phosphorus activity. Therefore, for calcareous soil, fertilizers need to be chosen that can maintain phosphorus activity for a long time.

This study investigated the long-term effects of five different phosphorus (P) fertilizers (Poly P, Ca-Mg P, SSP, MAP, and DAP) on crop yields during the winter wheat–summer maize rotation from 2017 to 2021. Our findings revealed that Poly P, MAP, and SSP significantly increased wheat and maize yields compared to Ca-Mg P and DAP. Particularly, the four-year average yield of Poly P was the highest, consistent with previous studies [39]. Poly P, with its slow-release properties, proved to be well-suited for loess soil under wheat–maize rotation. Although aboveground biomass showed no significant difference across treatments from 2017 to 2020, Poly P significantly influenced wheat thousand grain weight (TGW) from 2019 to 2021.

Long-term absence of P fertilization led to a significant reduction in crop yield, underscoring the importance of P fertilization. Interestingly, our results contrasted with another study [40], possibly due to variations in P fertilizer efficiency in soils with different pH levels. Overall, Poly P demonstrated strong aftereffects, enhancing crop nitrogen (N) utilization efficiency during the second topdressing. Furthermore, differences in P uptake by crops at the jointing stage significantly influenced wheat yield, while maize 1000-grain weight was notably affected by P fertilizer.

The absorption of nitrogen and phosphorus by crops also varies, and the impact of different fertilizer treatments on the nitrogen absorption process in crops is more complex than that of phosphorus. Poly P can exert its strong aftereffect to make crops use N in the second topdressing more efficiently [41]. There are significant differences in the accumulation patterns of phosphorus and nitrogen fertilizers. DAP treatment accumulated the most nitrogen in the tillering stage but only ranked fourth for nitrogen accumulation in the material stage. Similarly, DAP accumulated the most nitrogen in the V12 stage but only ranked fifth for nitrogen accumulation in the material stage. Although there is a synergistic absorption of nitrogen and phosphorus over a longer time scale, nitrogen and phosphorus exhibit allometric distribution in a shorter period of time. This allometric allocation will be reflected in the development of specific organs. There was no significant difference in

biomass between DAP and other phosphorus fertilizer treatments, but the thousand grain weight and number of grains per spike were significantly lower than other phosphorus fertilizer treatments. It can be considered that during the flowering and filling stages, DAP experiences insufficient nutrient absorption.

4.2. Long-Term Effects of Total P and Olsen-P on Soil

Different P fertilizers have different effects on the changes in soil P content due to their different properties. The TP and Olsen-P will decrease year by year under the non-application of P fertilizers due to the crops taking away part of the soil P. We found that the TP and Olsen-P in the soil can still maintain a relatively stable level, although the amount of P fertilizer applied was much lower than the traditional amount (200–300 kg ha^{-1}) of P applied in the local area. Our experiment was only conducted for four years and cannot fully demonstrate the impact of the more long-term use of a single phosphorus fertilizer variety on the soil. Azeez et al. [42] found the content of available P reduced by 56% when withholding P application for 20 years. We found that P depletion accelerated further in the presence of N fertilizer. In addition, we found that soil available P after harvest was not positively correlated with crop yield. Soil Olsen-P of DAP was higher during the maize season than in other soils. It also has a great relationship with the P absorption capacity of crops and the transformation of P fertilizer in soil.

Our study also found that the law of phosphorus fertilizer activity is not the same in the harvest seasons of wheat and corn, which may be related to the climate difference between the wheat growth season and the corn growth period and may also be related to the C3 and C4 characteristics of plants. The growing season of wheat is long (about eight months), but the average temperature is low and the rainfall is less, so the absorption rate of phosphorus may be slower. The growth period of maize is short (only four months), but the average temperature during this period is higher and there is more rainfall, so the absorption rate of phosphorus may be faster. The differences in duration, temperature, soil moisture, and type of phosphate fertilizer lead to differences in their binding rate with the carbonate in the soil. The difference in crop type may also lead to the difference in root exudates, which affects the combination of carbonate and phosphorus in the soil to form phosphate, resulting in the different effects of fertilizer on soil phosphorus in the harvest period of different crops.

4.3. Mechanism of Different P Fertilizers on Increasing Crop Yield

The PCA results showed a poor correlation between AP and GY. However, due to the use of Olsen-P at the end of the growing season in PCA, it cannot reflect the data of the growth process. Therefore, to fully consider the impact of Olsen-P on yield, it is necessary to have an understanding of the dynamic changes in Olsen-P.

Over time, the changes in Olsen-P content in soils treated with different phosphate fertilizers vary greatly (Figure S1). Phosphate fertilizer effectiveness decreased after application. After 80 days of fertilization, the Olsen-P of DAP was the same as with CK. The difference in the rate of change in Olsen-P content caused by the different types of phosphorus fertilizers has an impact on the differences in crop yield. For example, SSP is lower than DAP 40 days after fertilization but higher than DAP 80 days after fertilization. The yield was higher than DAP, but the thousand grain weight was lower than DAP. The formation of grain quantity is due to having a higher phosphorus content, which is lower during yield formation. Different P fertilizer properties influenced wheat and maize spike numbers, 1000-grain weight, and nutrient absorption capacity, collectively impacting yield variations [43].

In alkaline soil, the decrease in Olsen-P using Poly P treatment is slower, and the yield, biomass, and thousand grain weight of Poly P were higher than those of other treatments. This may be because Poly P is a polymer compound that has poor binding with calcium carbonate in alkaline environments and can retain more Olsen-P for plant absorption.

Moreover, the proportion of grain yield to aboveground weight varied (harvest index) under different P treatments (Figure S2), indicating differences in nutrient transport. Wheat treated with phosphorus fertilizer has a higher harvest index than the treatment without phosphorus fertilizer, Zero P, but lower than CK. There is a synergistic effect between nitrogen fertilizer and phosphorus fertilizer in the process of yield formation. The wheat harvest index of the Poly P treatment was higher than that of other treatments. The absorption of phosphorus has a significant effect on the formation of maize grain yield.

5. Conclusions

In the alkaline soils of the Loess Plateau, the application of different types of phosphate fertilizers leads to variations in the soil–plant phosphorus cycle. Due to the differences in the types of phosphate fertilizers, the processes of phosphorus adsorption and release in the soil vary, resulting in disparities in the content, activity, and composition of phosphorus in the soil during various growth stages of the crops. This, in turn, leads to differences in the absorption of phosphorus by the plants during different production stages, affecting yield components such as crop biomass, grain number per ear, and thousand-grain weight and, ultimately, impacting the yield.

Four-year-long experiments have underscored the importance of applying phosphorus fertilizers to maintain soil phosphorus levels in the alkaline soil environment of the Loess Plateau. With an eye on enhancing soil fertility and optimizing grain yield, Poly P, SSP, and MAP are found to be more suitable for application in the summer maize–winter wheat rotation system on loess soil than CaMg P and DAP. Among these, Poly P stands out as the most effective in optimizing the harvest index and increasing crop yield.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14061317/s1, Figure S1: The relationship between the availability and time of different phosphate fertilizers applied to soil; Figure S2: Ratio of grain yield to aboveground biomass. (A) wheat; (B) maize. The dark area (above position) is the proportion of grain content; The bright area (below) is the proportion of weight above ground.

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