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Combined application of biochar and phosphorus influenced maize production and soil properties in the Yellow River Delta: a comparison between contrasting weather conditions

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Abstract: The Yellow River Delta, an important area of reserved arable land resources in China, is faced with the problem of crop productivity being typically limited by low soil quality. Developing techniques that raised crop yield without environmental damage was critically needed. To date, the knowledge about the joint impacts of biochar (C) and phosphorus (P) addition on soil properties and maize production under different weather conditions in this area is seriously lacking. Consequently, a full factorial field experiment including three biochar intensities (0 (C_0), 5 000 (C_1), and 10 000 (C_2) kg/ha), three phosphorus fertilisation levels (0 (P_0), 60 (P_1), and 120 (P_2) kg P/ha), and their combinations was conducted in Binzhou, Shandong province of China from 2021 to 2022. Compared to 2022, the maize yield was dramatically reduced in 2021 (with a 35% mean decrease) due to excessive rainfall in the maize reproductive growth stage ($P < 0.01$). C addition caused greater proportions and contributions of dry matter and nutrient remobilisation from pre-anthesis vegetation organs to grain. Subsequently, maize yield was much more promoted in 2021 (23%) than in 2022 (5%) by adding C, in which the discrepancies between C_1 and C_2 were relatively small and insignificant. On the other hand, these corresponding effects of P and C × P were relatively modest. From the soil perspective, soil physical (hydraulic conductivity (*Ks*) and bulk density) and chemical properties (soil organic carbon, total N, and soil available N) were significantly improved by C addition ($P < 0.01$). More importantly, we detected negative interactions of C × P on soil available P and phosphorus activation coefficient ($P < 0.01$), as soil available P was lowered with more input of C and P together (particularly under P_2 series). The two-year outcomes suggested that C addition could enhance maize growth and ensure crop yield stability. Still, the combined incorporation of this kind of C and P (especially for C_2P_2) was not recommended in the saline-alkali land. The present study delivered useful insight into the rational utilisation of C and P fertilisers in the Yellow River Delta.

Keywords: bio-waste; soil fertility; unfavourable weather conditions; multiple seasons; fertiliser management

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Biochar (C), produced from bio-waste (straw, branches, or manure) under oxygen-limited pyrolysis, was a carbon-rich material and typically exhibited a porous structure, with high surface area (Atkinson et al. 2010, Luo et al. 2017). Generally, biochar amendment into the soil could improve soil fertility and elevate crop productivity (Faloye et al. 2019). Meta-analysis pointed out that the application of biochar could increase crop yield by a mean of 10%, though the effect had a large range (from –28% to 39%) (Gul and Whalen 2016). Apart from directly supplying nutrients and increasing soil organic carbon (SOC), biochar could reduce soil compaction, raise water holding capacity, and improve saturated hydraulic conductivity. Moreover, biochar enhanced mineral fertiliser use efficiency and reduced the risk of environmental loss by greenhouse gas emissions and leaching (Haider et al. 2022).

Phosphorus (P) is an essential and limiting macronutrient for crop growth. Thus, intensive P fertilisation has been carried out in many arable soils in China. However, more than 80% of applied P fertilisers could not be used by plants as they were fixed *via* sorption, precipitation, or microbial immobilisation in soil (Haider et al. 2022). Accordingly, surplus P in arable soils could lead to eutrophication of receiving water bodies through leaching and runoff (Ghodszad et al. 2021). Adding biochar could affect these processes and regulate plant-available P for crop production. However, the affected magnitude and even direction were very complex, depending on the kinds of P source, biochar types, and soil chemical properties (Zhang et al. 2025). A recent meta-study suggested that biochar stimulated P availability in acidic (pH < 6.5) and neutral (6.5–7.5) soils, but there was no significant effect in alkaline soils (> 7.5) (Glaser and Lehr 2019). The relatively small number of records and high variability within the alkaline soil group hinted that more case study was urgently required to probe the interactions of P fertilisers and biochar amendment in alkaline soil. Specifically, P sorption and desorption experiments also indicated that contradictory effects of the biochars on P availability existed, particularly in alkaline soil, as the regulation mechanisms were more complex than in acidic soil (Bornø et al. 2018, Ghodszad et al. 2022). These results emphasised that optimal use of biochar with P fertilisers in an alkaline environment required more attention. Furthermore, how the weather conditions modulated the performance of biochar and P fertilisers has largely remained scant. The outcomes, used to improve the crop simulation model, would lessen uncertainties when predicting the crop yield under climate change scenarios (Li et al. 2019).

Due to China's huge population base and rapid economic development, keeping a sufficient grain supply is vital to ensure national food security. The Yellow River Delta was a newly born wetland in coastal areas, where a large proportion of land had been reclaimed for arable land (Han et al. 2014). These fields were characterised by saline-alkali soil, with relatively high pH, excessive soluble salts, unsuitable soil physical properties, and poor soil fertility, which constrained crop production (Luo et al. 2017, Yang et al. 2021, Zhu et al. 2022). Even so, this area possessed great potential for grain production if reasonable agronomy techniques were employed (Li et al. 2011). To date, information about the interactive impacts of biochar and P addition on maize production and related soil properties in the Yellow River Delta remains inadequate to the best of our knowledge.

The purpose of this study aimed to (1) assess the impacts of C and P addition and their combination on maize production and nutrient accumulation, particularly under different weather conditions; (2) analyse biomass and nutrient remobilisation and reveal the regulation of C and P addition; (3) characterise the changes of soil physical and chemical properties (particularly for soil P status) and explain their contributions to maize production. Logically, we intended to elucidate the variations of maize yield from the perspectives of plant and soil processes. Identifying these mechanisms is critical to optimising the use of C and P fertilisers in this region.

MATERIAL AND METHODS

Study site. This experiment was conducted at Guoma Village (38.0°N, 117.6°E) of Xiaobotou Town, which was located in Wudi County, Binzhou City, Shandong Province, China. The trial site featured a typical continental monsoon climate, with a mean annual temperature of 13 °C. The maximum temperature is 41 °C in July and the minimum is –10 °C in January. The rainfall is mainly concentrated between June and September, with a mean annual precipitation of about 570 mm. The soil in this study site is characterised as a coastal salinised flavour aquic soil, and the soil texture was silty clay loam with low sand content and a high proportion of clay. This soil belongs to Cambisols, as classified by the WRB system (IUSS 2006), and is

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the typical soil group for agricultural use in this area. Some of the initial properties of the topsoil (0–20 cm) were measured before the experiment, with a pH of 8.12, SOC of 6.05 g/kg, total N of 0.65 g/kg, total P of 0.42 g/kg, and available phosphorus of 13.74 mg/kg, respectively. In the study site, the winter wheat-summer maize rotation was used. In October of 2019, the field experiment was initially set up to identify the joint effects of biochar and phosphorus addition on crop production.

Experimental design. To explore the alone and combined influence of C and P addition on maize growth. A 2-factor, 3-level complete factorial design was employed, including three biochar addition levels and three P intensities. The biochar levels (0, 5 000, and 10 000 kg/ha) were recorded as C_0, C_1, and C_2, respectively, while P intensities (0, 60, and 120 kg P/ha) were represented as P_0, P_1, and P_2, respectively. Thus, there were nine treatments in this trial. Every treatment was repeated three times, and there were 27 experimental plots. We used a randomised complete block design, and the size of each plot was 16.2 m^2 (1.8 m × 9 m), with an interval of 1 m between plots as a buffer zone. The same dose of N and K fertilisers was applied at the rate of 200 kg/ha and 60 kg/ha for all treatments. The biochar was made through pyrolysis of wheat straw at 450–500 °C with a residence time of 1.5 h under anoxic conditions (Zedi Agricultural Technology Company, Zhengjiang, China). The biochar showed a pH of 7.9 and had 529 g/kg total C, 8.25 g/kg total N, 2.17 g/kg total P, and 18.97 g/kg total K. The density of biochar was 589 kg/m^3. The additional C, N, and P supplied by biochar alone were 2 645 kg/ha, 41.25 kg/ha, and 10.85 kg/ha, respectively, for C_1 treatment; and 5 290 kg/ha, 82.50 kg/ha, and 21.70 kg/ha, respectively, for C_2. All the biochar was screened through a 2-mm sieve before application to soil. Urea, calcium superphosphate, and potassium chloride were used as N fertiliser, P fertiliser, and K fertiliser, respectively. The sowing density of maize was according to the regional recommendation (66 000 plants/ha) with a row interval of 60 cm, and the maize cultivar used for the experiment was Zhengdan 958, which possessed great yield potential and high climate and soil adaptability.

The plants were sown on June 20 and harvested on September 27 in 2021. The corresponding dates were June 17 and September 19 in 2022. For each June before maize sowing, the biochar and mineral fertilisers were applied as the basal fertilisers, which were broadcast uniformly on the soil surface and then mixed and incorporated into the 0–20 cm layer of soil using a rotavator. There was no topdressing and irrigation across the growth period. To control the weeds and pests, herbicides and pesticides were sprayed according to the local suggestions.

The data on monthly precipitation and monthly mean air temperature were collected from the local meteorological bureau (about 1.6 km from the experimental field), using an automated weather station.

Sampling and analysis methods. At physiological maturity, maize ears were sampled to calculate grain yield. The ears were manually harvested in a 6 m^2 area (two inner rows of the plot, each 5 m long) in each plot with three replicates.

We tagged the appearance-consistent maize plant using a red line during the twelve-leaf stage. These plants were selected in the inner row of the plot, and the 5 m-long row employed for estimating grain yield remained unsampled. At the silking and physiological maturity stages, six plants were randomly collected from tagged plants by cutting from the soil surface in each plot. The plant samples at the silking stage were directly used (all defined as vegetative tissue), and the plant samples at the physiological maturity stage were separated into grain and vegetative tissues that included stalks (leaf sheaths, tassels, husks, and cobs) and leaves. All samples were immediately oven-dried at 105 °C for 30 min and then dried at 70 °C to a constant weight. These materials were weighed to get dry matter weight (DM). Then, an electric mill ground the materials into a fine powder. After the samples were digested with H_2SO_4-H_2O_2, total N and P content were determined by the Kjeldahl and molybdenum blue methods, respectively. Based on the measured plant DM and N or P content, we could calculate DM remobilisation efficiency (DMRE), N remobilisation efficiency (NRE) and P remobilisation efficiency (PRE); we then estimated DM remobilisation contribution to grain (DMRC), N remobilisation contribution to grain (NRC) and P remobilisation contribution to grain (PRC). These calculation methods were according to the suggestions of previous studies (Yuan et al. 2024, Chen et al. 2015).

DM (N or P) remobilisation amount (g/plant) = DM (N or P) accumulation of vegetative tissues at the silking stage (g/plant) – DM (N or P) accumulation of vegetative tissues at the maturity stage (g/plant);

DM (N or P) remobilisation efficiency (RE, %) = DM (N or P) remobilisation amount/DM (N or P) accumulation amount at the silking stage × 100;

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DM (N or P) remobilisation contribution to grain (RC, %) = DM (N or P) remobilisation amount/grain DM (N or P) accumulation at maturity stage × 100;

Harvest index (HI, %) = grain DM at the maturity stage (g/plant)/whole plant DM at the maturity stage (g/plant) × 100

Due to the severe weather conditions of 2021, collecting soil samples in the vigorous plant growth stage was impossible. Consequently, we did not sample soil in 2021. During the silking stage in 2022, we collected and analysed soil samples (0–20 cm layer). Three soil cores (2 cm diameter) were taken randomly from each plot and then mixed into a composite sample. The soil sample was air-dried and passed through a 2 mm sieve for further chemical analysis. Briefly, SOC was determined by sulfuric acid and potassium dichromate oxidation method (Nelson et al. 1996), total N by the Kjeldahl method, available N content by the alkali diffusion method (Bremner and Tabatabai 1972), and total P and available P contents were measured using molybdenum blue method after digested H_2SO_4-$HClO_4$ and extraction of 0.5 mol/L sodium bicarbonate, respectively (Olsen 1954). Based on the soil total P and available P contents, we could calculate the phosphorus activation coefficient (PAC) as suggested by Zhang et al. (2020).

PAC = available P/total P × 100

Detailed steps of the above chemical analysis were exhibited in a previous paper (Yan et al. 2023). A 1:5 (*w*/*v*) soil-to-water ratio was used to measure the pH (PHS-3C pH meter, Shanghai, China) and electrical conductivity (EC) (4501 conductivity meter, Jenway, UK) of soil samples, as described by Rhoades (1996).

For the physical characters, we used a metal ring (with a volume of 100 mL) to take three replicated, undisturbed soil samples from each plot. The bulk density (BD) of soil and soil water content were measured based on the oven-dried weight (105 °C) of the undisturbed soil sample, and the total porosity was calculated from the bulk density, assuming a particle density of 2.65 g/cm^3. Subsequently, the saturated hydraulic conductivity (*Ks*) was estimated using the constant head method. The measurements of physical characteristics were referred to Bao (2000).

Statistical analysis. One-way analysis of variance (ANOVA) followed by mean comparisons with Duncan's *HSD* (honestly significant difference) test was conducted to detect the difference between the tested parameters by C and P addition. Across the two-year study, repeated-measures ANOVA was carried out to investigate the influence of the measured year (Y), the overall impact of C and P addition, and their interactions. Two-way ANOVA was used to identify the effect of C and P addition and their combination on soil parameters in 2022. Statistical analysis and graphing were performed by SPSS V26.0 (IBM, Chicago, USA) and Origin 9.0 (OriginLab Corporation, Northampton, USA), respectively.

RESULTS

Change in maize yield, nutrient accumulation, and harvest index. From June to September, the air temperature of 2021 and 2022 was similar, while the cumulative precipitation of 2021 (727 mm) was much larger than that of 2022 (566 mm) (Figure 1). The discrepancy mainly occurred in August and September, with 246 mm and 239 mm for 2021, while 95 mm and 21 mm for 2022. The heavy rainfall in this late growing season of maize led to excess soil water content and

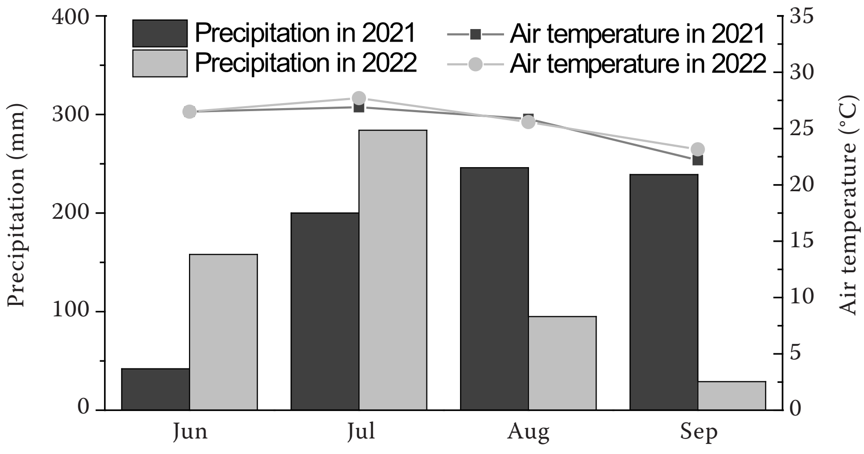

Figure 1. The monthly precipitation and monthly mean air temperature during the growth period of summer maize in 2021 and 2022

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even caused waterlogging before harvest in this region (Binzhou News 2022). Because the long-term mean annual precipitation was about 570 mm according to the meteorological record, our study in these two years offered an opportunity to compare and identify the performance of C and P supplements on maize production under contrasting weather conditions (excessive rainfall *vs.* normal rainfall).

The ANOVA results showed that across the two-year data set, the measured Y had a significant impact on maize grain yield and harvest index ($P < 0.01$), as these parameter values were more remarkably depressed in 2021 than in 2022 (Figure 2A, B). We also found that C rather than P addition had a significantly positive impact on grain yield ($P < 0.05$) (Figure 2A). More importantly, the Y × C interaction effect on grain yield was significant ($P < 0.05$) (Figure 2A), as the enhanced magnitude of grain yield induced by C addition was much larger in 2021 than in 2022. On average, C_1 and C_2 increased the yield by 20.5% and 24.8%, respectively, compared to C_0 in 2021, while the corresponding values in 2022 were only 5.3% and 3.8%, respectively (Figure 2A). For the harvest index, P addition could significantly stimulate its value if putting two-year data together ($P < 0.05$), while the corresponding effect of C addition was not discovered (Figure 2B).

The measured Y and C additions showed significant N and P accumulation roles in the silking and maturity stages, respectively ($P < 0.01$). The nutrient accumulation was lower in 2021 compared to 2022, implying that unfavourable weather conditions hindered the uptake of nutrients from the soil (Figure 2C–F). However, C addition could help crop growth by absorbing relatively more N and P under severe weather conditions ($P < 0.01$). Irrespective of P treatment, silking stage N accumulation of C_1 and C_2 was 24.4% and 27.9% larger than C_0 in 2021, and the increased extent of 2022 was 13.8% and 14.5%, respectively (Figure 2C). For P accumulation at the silking stage, the corresponding increased extent was 30.7% and 35.1% in 2021, and 16.5% and 17.3% in 2022 (Figure 2D); for P accumulation at the maturity stage, the enhanced magnitude by C addition was 29.6% and 38.2% in 2021, and 18.0% and 18.8% in 2022 (Figure 2F). The P addition showed a boosted tendency for N and P accumulation, especially under C_0 and C_1 conditions, though no statistical differences were detected by ANOVA (Figure 2C–F).

Biomass and nutrients remobilisation. ANOVA suggested that the effect of study Y significantly affected dry matter remobilisation efficiency (DMRE) and dry matter remobilisation contribution to grain (DMRC) ($P < 0.01$). On average, DMRE and DMRC exhibited greater values in 2021 than in 2022 (Figure 3A, B). Furthermore, C addition could markedly stimulate DMRE and DMRC (particularly under lower added P level) in 2021, but these effects appeared to be reversed in 2022. Consequently, a significant Y × C interaction effect on DMRE and DMRC was found ($P < 0.01$), but the overall two-year impact of C was not significant (Figure 3A, B). On the other hand, DMRE and DMRC showed an increased trend with increased use of P in both 2021 and 2022 (Figure 3A, B).

Study Y had a significant influence on N remobilisation efficiency (NRE) and N remobilisation contribution to grain (NRC) ($P < 0.01$), with greater values in 2022 than in 2021(Figure 3C, D). In addition, significantly stimulated NRE and NRC ($P < 0.01$), especially in 2021. In addition, this trend could also help to increase NRE and NRC; this trend was more dramatic for NRE and NRC under C0 and C1 conditions in 2021, and NRE and NRC under C0 conditions in 2022 (Figure 3C, D). P remobilisation efficiency (PRE) was significantly affected by study Y and Y × C interaction ($P < 0.01$) (Figure 3E). The mean value of PRE was greater in 2022 than in 2021, and C addition had a positive role on PRE in 2021, which seemed to be reversed in 2022 (Figure 3E). Because P remobilisation contribution to grain (PRC) showed high variability, the factors with significant influence were not distinguished. However, we could still find that PRC was generally heightened with increased use of P (Figure 3F).

Changes in soil properties. There were no significant effects for the soil physical properties for P addition, and the interaction of C × P was also not found. On the contrary, the C addition exerted a marked impact on these characters ($P < 0.01$) (Table 1). On average, BD was lowered by 6.9% and 13.3% for C_1 and C_2, compared to C_0, while porosity exhibited an increasing trend. The soil water content was slightly heightened by adding C, with values of 16.5% for C_0, 17.9% for C_1, and 19.5% for C_2. *Ks* was more notably raised with increased use of C. The *Ks* of C_1 and C_2 were 38.1% and 84.8% greater than C_0, regardless of P treatment.

For the soil chemical properties, C addition showed a significant influence on pH, EC, SOC, total N, and available N ($P < 0.01$) (Table 2). Soil pH was slightly reduced under the C addition condition,

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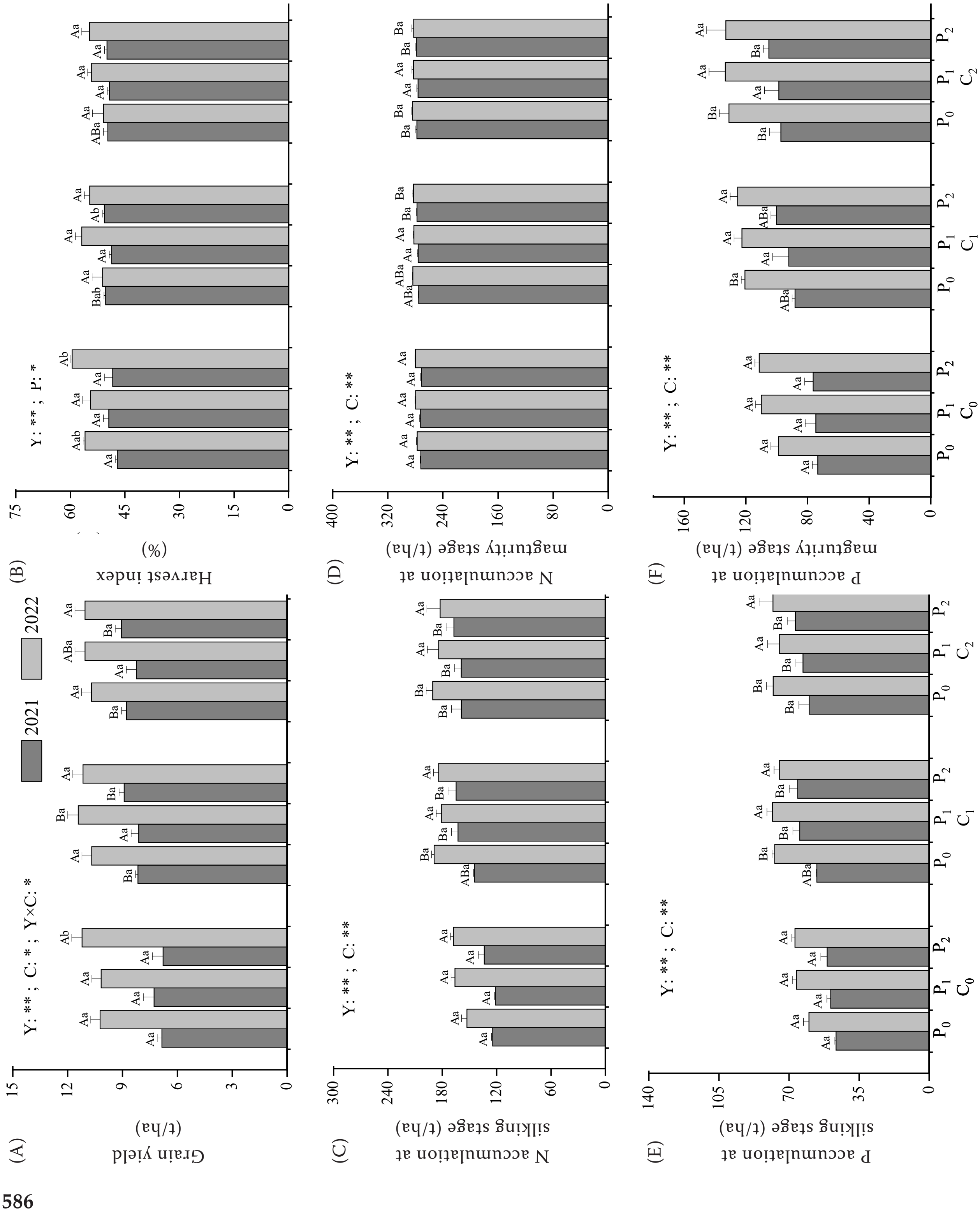

Figure 2. Impacts of biochar (C) and phosphorus (P) addition and their combination on (A) grain yield; (B) harvest index; (C, D) nitrogen (N), and (E, F) phosphorus (P) accumulation at the silking stage and the maturity stage of summer maize in 2021 and 2022. The vertical bars denote the standard errors. Within the same year, different uppercase letters implied the significant difference (at the 0.05 probability level) between C addition treatments under the same added P level, while different lowercase letters indicated the significant difference (at the 0.05 probability level) between P addition treatments at the same added C level. By repeated-measures ANOVA, * and ** denoted the factor played a significant effect at the 0.05 and 0.01 probability levels, respectively. Factors with non-significant effects at the 0.05 level were not shown

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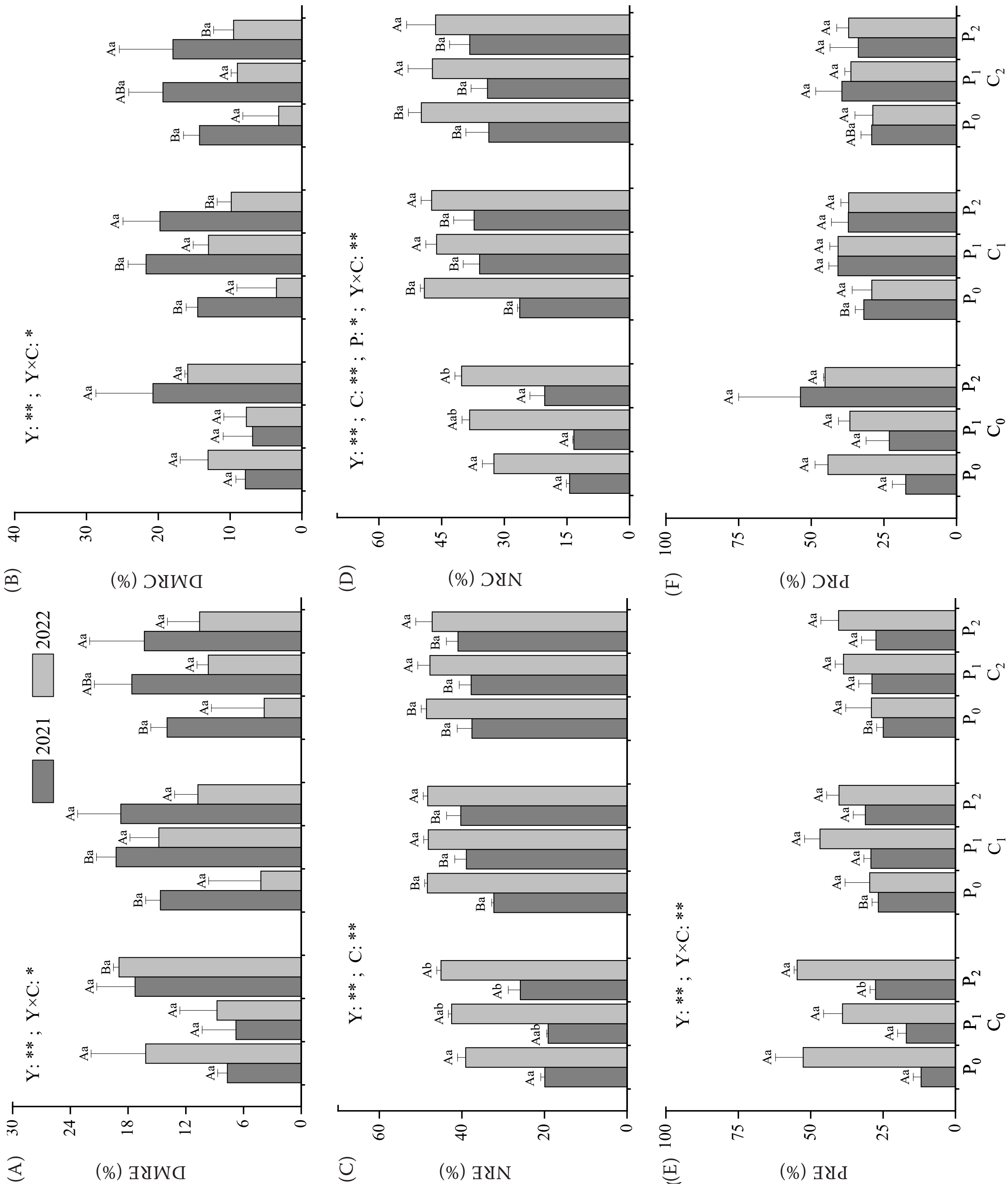

Figure 3. Impacts of biochar (C) and phosphorus (P) addition and their combination on dry matter remobilisation efficiency (DMRE) (A) and dry matter remobilisation contribution to grain (DMRC) (B), N remobilisation efficiency (NRE) (C) and N remobilisation contribution to grain (NRC) (D), P remobilisation efficiency (PRE) (E) and P remobilisation contribution to grain (PRC) (F) of summer maize in 2021 and 2022 The vertical bars denote the standard errors. Within the same year, different uppercase letters implied the significant difference (at the 0.05 probability level) between C addition treatments under the same added P level, while different lowercase letters indicated the significant difference (at the 0.05 probability level) between P addition treatments at the same added C level. By repeated-measures ANOVA, * and ** denoted the factor played a significant effect at the 0.05 and 0.01 probability levels, respectively. Factors with non-significant effects at the 0.05 level were not shown

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Table 1. Impacts of biochar (C) and phosphorus (P) addition and their combination on soil physical properties

Year	Treatment		BD (g/cm^3)	Porosity (%)	*Ks* (mm/min)	Soil water content (%)
2022	C_0	P_0	1.36^{aB}	48.7^{aA}	0.33^{aA}	15.4^{aA}
		P_1	1.40^{aB}	47.2^{aA}	0.37^{aA}	16.6^{aA}
		P_2	1.46^{aC}	44.9^{aA}	0.35^{aA}	17.5^{aA}
	C_1	P_0	1.29^{aAB}	51.3^{aAB}	0.49^{aB}	17.8^{aB}
		P_1	1.32^{aAB}	50.2^{aAB}	0.45^{aB}	17.3^{aAB}
		P_2	1.32^{aB}	50.2^{aB}	0.51^{aAB}	18.6^{aAB}
	C_2	P_0	1.22^{aA}	54.0^{aB}	0.65^{aC}	19.4^{aC}
		P_1	1.21^{aA}	54.3^{aB}	0.67^{aC}	19.2^{aAB}
		P_2	1.23^{aA}	53.6^{aC}	0.62^{aB}	19.9^{aB}
ANOVA	C		**	**	**	**
	P		ns	ns	ns	ns
	C × P		ns	ns	ns	ns

BD – bulk density; Ks – hydraulic conductivity

with mean values of 8.04 for C_0, 7.95 for C_1, and 7.90 for C_2. The use of C boosted EC, SOC, total N, and available N, and these parameters of C_1 were 14.7, 57.9, 7.88, and 18.94% larger than C_0, and the corresponding magnitude was 22.2, 128.9, 26.6, and 55.7% for C_2. Additionally, there was an increased trend of SOC, total N, and available N with increasing use of P. More interestingly, C addition and P addition alone displayed a significant effect on total P, available P, and PAC ($P < 0.01$), and their combination exerted a negative interaction on available P and PAC ($P < 0.01$) (Table 2). Specifically, the available P and PAC of P_1 under the C_0 condition were 200.4% and 163.6% larger relative to P_0, and for P_2, the changes were 200.0 % and 148.5% larger than P_0. The increased patterns were weakened when applying more C. Under the C_1 condition, the available P and PAC of P_1 were increased by 128.8% and 80.0% respectively, and the corresponding values for P2 were only increased by 19.6% and decreased by 20.0% respectively. In contrast, in the C2 condition, the available P and PAC of P1 were increased by 19.4% and reduced by 15.0%, and P2 treatment depressed the corresponding values by 32.2% and 52.5%, respectively (Table 2).

Table 2. Impacts of biochar (C) and phosphorus (P) addition and their combination on soil chemical properties

Year	Treatment		pH	EC (dS/m)	SOC (g/kg)	Total N (g/kg)	Available N (mg/kg)	Total P (g/kg)	Available P (mg/kg)	PAC (%)
2022	C_0	P_0	8.27^{bB}	0.79^{aA}	6.12^{aA}	0.73^{aA}	18.25^{aA}	0.46^{aA}	15.26^{aA}	3.3^{aA}
		P_1	7.96^{aA}	0.78^{aA}	7.43^{aA}	0.85^{aA}	22.38^{aA}	0.52^{abA}	45.85^{bA}	8.7^{bA}
		P_2	7.91^{aA}	0.79^{aA}	7.17^{aA}	0.83^{aA}	25.67^{aA}	0.56^{bA}	45.78^{bA}	8.2^{bB}
	C_1	P_0	8.00^{aAB}	0.85^{aA}	10.27^{aB}	0.86^{abB}	25.64^{aAB}	0.53^{aB}	42.20^{aB}	8.5^{aAB}
		P_1	7.89^{aA}	0.93^{aAB}	10.57^{aB}	0.79^{aB}	25.16^{aAB}	0.63^{bB}	96.56^{bB}	15.3^{bB}
		P_2	7.98^{aB}	0.92^{aAB}	11.87^{bB}	0.95^{bB}	28.06^{aB}	0.74^{cB}	50.47^{aA}	6.8^{aAB}
	C_2	P_0	7.94^{aA}	0.89^{aA}	15.31^{aC}	0.97^{aA}	33.21^{aB}	0.58^{aB}	70.10^{bC}	12.0^{bB}
		P_1	7.98^{aA}	0.96^{aB}	15.67^{aC}	0.99^{aB}	34.57^{aB}	0.82^{bC}	83.68^{bB}	10.2^{bAB}
		P_2	7.79^{aA}	1.03^{aB}	16.44^{aC}	1.09^{aB}	35.48^{aC}	0.84^{bB}	47.51^{aA}	5.7^{aA}
ANOVA	C		*	*	**	**	**	**	**	**
	P		ns	ns	ns	ns	ns	**	**	**
	C × P		ns	ns	ns	ns	ns	*	**	**

EC – electrical conductivity; SOC – soil organic carbon; PAC – phosphorus activation coefficient

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DISCUSSION

Maize yield under contrasting weather conditions. Heavy rainfall caused severe decreases in maize production by up to 34% (17% on average) compared to normal yields by synthesising long-term trends across the United States (Li et al. 2019). Using controlled field experiments, a previous study reported similar results (Lone and Warsi 2009). In the unfavourable weather conditions of 2021, we also found that the maize yields were drastically suppressed by 22–42% compared to 2022. In general, the waterlogging induced by frequent extreme precipitation caused adverse effects on crop aboveground traits and thus reduced crop yield (Huang et al. 2022). Admittedly, the lack of light in cloudy and drizzly conditions could also inhibit flowering and pollination, leading to yield reduction (Uhart and Andrade 1995, Wang et al. 2006). Artificially manipulated experiments were needed to distinguish these compound influences of weather conditions. On the other hand, the high soil moisture caused a lack of oxygen, damaged plant roots, and restricted nutrient uptake, which finally depressed yield formation (Parent et al. 2008, Li et al. 2019). Even so, we detected that the C addition rather than P could promote grain yield more in 2021 than in 2022 (Figure 2A). The underlying mechanisms of the maize yield formation in response to added C and P under contrasting weather conditions were intended to be analysed based on crop and soil perspectives in the following section.

Accumulation and remobilisation of crop biomass and nutrients. As nutrient supply directly affected crop dry matter production, N and P accumulation patterns were similar to those of dry matter (Figure 2). The C addition raised the N and P accumulations. Other studies reported consistent results (Pandit et al. 2018), demonstrating that added C could ameliorate soil nutrient conditions (see next section). Although N and P accumulation were much lower in 2021 than in 2022, C addition promoted relatively more N and P accumulation than the C0 treatment, reflecting that the processes by which C addition modulates soil nutrient supply should differ between the contrasting weather conditions. In addition, there was an increasing trend of N accumulation with more use of P (particularly under C_0 treatment) (Figure 2C, F), probably because plants would develop a stronger root system that took up more N when using more P fertiliser (Dordas 2009). On the other hand, considering the two-year results, P additions had minimal effects on crop dry matter production, with a decrease of 1.23% for the P1 series and an increase of 0.56% for the P_2 series. A recent meta-study analysing global cropland data suggested P additions increased plant production by 13.9% (Hou et al. 2020). The weak response of crop production to two P addition levels within our case and compared to the global average value might imply that most of the P fertiliser was sorbed by the saline-alkali soil.

The source-sink relationship theory contended that total shoot dry matter denoted the "source" of photoassimilate, while harvested grain meant the "sinks". As the harvest index was the proportion of the seed mass to the whole crop value at maturity, this index mirrored the cumulative balance between the source and sink (Smith et al. 2018). The lowered harvest index in 2021 implied that the crop sink was more greatly depressed than the source under such unfavourable weather conditions (Yang et al. 2010). We also detected that this index seemed to be raised with more use of C in 2021, and the opposite effect was observed in 2022 (Figure 2B). This phenomenon hinted that the strengths of the source and sink were mediated with increased use of C, but the extent of the effect and even the direction of the two organs differed between the two years.

The variability within the group for DMRE and DMRC was higher than that of other crop parameters because they were computed from the differences in dry matter weight between the silking stage and maturity stage, but not directly measured (Gallais et al. 2007). However, we could still capture the impacts of study Y, adding C and P (Figure 3A, B). Generally, the yield formation of cereals was derived from two parts: stored assimilates in the vegetative organs before silking and direct photosynthate during the grain-filling stage (Fazel and Lock 2011, Zhang et al. 2012). Previous theory corroborated that more reserved assimilates would be remobilised if the post-silking photosynthesis product could not satisfy the requirements of grain growth (Uhart and Andrade 1995, Dordas 2009, Asseng et al. 2017, Kitonyo et al. 2018). On average, DMRE and DMRC exhibited much larger values in 2021 than in 2022, demonstrating that the formation of photosynthesis products during the grain-filling stage was limited by excessive rainfall. Accordingly, DMRE and DMRC in 2021 were further enhanced if more C was added (Figure 3A, B), indicating this factor would be conducive to alleviating this limitation by remobilising assimilates stored

https://doi.org/10.17221/268/2025-PSE

in vegetative organs. Similar C-addition effects had been reported in other case studies (Tian et al. 2021, Ghaedi et al. 2024). However, under normal weather conditions, DMRE and DMRC gradually declined with increased application of C (Figure 3A, B). The results reflected that this adaptive compensatory adjustment was not needed in 2022. Our two-year results were consistent with the previous inference that the contribution of pre-silking assimilates to grain was critical for ensuring crop yield if adverse climatic conditions hampered leaf photosynthesis, or water and mineral uptake from the roots (Arduini et al. 2006). We further emphasised that C addition could strengthen this mechanism, which is essential for maintaining crop yield steadily. Interestingly, P addition consistently enlarges DMRE and DMRC during the two-year study (Figure 3A, B). These contrast patterns implied that the modulating mechanism of added P on dry matter remobilisation might differ from that of C.

The nutrient (N and P) remobilisation was enhanced by adding C in 2021 (Figure 3C, E). Previous researchers had reported that C addition led to higher NRE and NRC (Xiao et al. 2017). They explained that the higher N demand due to grain growth in the added C treatments stimulated more translocated N despite the higher post-silking N accumulation already achieved (Xiao et al. 2017). Nevertheless, the average nutrient values (especially for N) remobilisation were larger in 2022 than in 2021 (Figure 3C, E). This pattern was contrary to that of DM (Figure 3A). The reason had been stated that remobilised C was mostly derived from the crop stem, which was greatly affected by grain sink strength; in contrast, the primary origin of remobilised N was derived from both stems and leaves, which was rather independent of sink strength (Masoni et al. 2007). It was further found that P addition positively affected nutrient (N and P) remobilisation (Figure 3C, E). This trend was at odds with previous researchers (Barbottin et al. 2005, Dordas 2009), who pointed out that the added P treatments did not affect the contribution of pre-anthesis N and P to grain filling. These conflicting responses might be attributed to differences in crop variety or initial soil condition.

Overall, the different responses of DM remobilisation to C and P addition, and the discrepancies between DM and nutrient remobilisation under contrasting weather conditions, need deep exploration in further research. The underlying mechanism should be considered to consummate the crop growth simulation model.

Soil physical and chemical properties. Soil physical properties were improved by C addition (Table 1) because BD was gradually reduced and total soil porosity was subsequently increased when more C was used (Wan et al. 2024). The reason was that biochar possessed high internal porosity or biochar particles were conducive to creating larger soil macropores surrounding themself (Faloye et al. 2019). Meanwhile, biochar might favour the formation of soil aggregates, which was expected to lower BD and heighten soil porosity (Wang et al. 2017). As the changed soil porosity could regulate the soil moisture retention capacity (Xiao et al. 2016, Wang et al. 2017), larger soil water content was detected with increased input of C in our study. The increased soil water storage could be available for crops if needed, and buffer the uncertainties of rainfall patterns, which was very important for rain-fed agroecosystems or arid environments (Xiao et al. 2016, Wan et al. 2024). In sandy soil, biochar could decrease the *Ks* (Barnes et al. 2014) or did not change the *Ks* (Jeffery et al. 2015); while for clay loam soil as in our study, the *Ks* was elevated with more added C (Table 1), which was in line with the previous studies (Acharya et al. 2024). The possible reason was that relatively larger biochar particles substituted the soil clay particles, which increased the macro-porosity and subsequently raised soil *Ks* (Xiao et al. 2016).

In our case study, the maize yield was lowered by 22–42% (with a mean of 35%) in 2021 relative to 2022. As discussed in the above section, this extent of yield reduction induced by heavy rainfall was at the high-end values in the previous meta-analysis (Li et al. 2019). The high losses of maize yield might be due to the soil texture (silty clay loam) in the study site, which had low hydraulic conductivity. A synthesis of investigations across the US also confirmed that corn produced on claypan soils was more susceptible to precipitation extremes (Youssef et al. 2023). The increase of *Ks* in C_1 and C_2 was 38.1% and 84.8% greater than that of C_0, regardless of P treatment. The increased magnitude was more noticeable than other soil physical parameters. Thus, it was logically inferred that apart from providing additional nutrients that were conducive to maize growth and yield (such as in 2022) (Table 2), C addition could accelerate the rate of water infiltration (as indicated by increased *Ks*), which subsequently reduced the risk of waterlogging as suggested by other researchers (Blanco-Canqui et al. 2011, King et al. 2020). This process might contribute to the phenomenon that

https://doi.org/10.17221/268/2025-PSE

the enlarged magnitude of grain yield by C addition was much greater in 2021 than in 2022, though the maize had experienced 2021 superfluous rainfall.

The feedstock character (particularly chemical composition) and pyrolysis conditions controlled the extent and direction of biochar amendment on soil pH (Wang et al. 2020). Generally, biochar has higher alkaline mineral contents after pyrolysis, which reduces the H^+ concentration and increases soil pH. However, we found a slightly decreased trend of pH under the added C treatment (Table 2). Fan et al. (2017) pointed out that organic acids or compounds in biochar derived from crop straw might neutralise the alkalinity during the pyrolysis, and this kind of biochar therefore had a limited or even reduced effect on pH. Consistent with earlier studies (Akbar et al. 2024), C addition, both with and without P fertiliser, caused an elevation in soil EC. This increase in EC can be attributed to the high concentration of soluble salts and calcium in biochar (Berek et al. 2018). C addition significantly positively affected soil nutrient availability (Table 2). This was because biochar itself is a direct source of nutrients. In our study, the inputs of N from C_1 (41.25 kg/ha) and C_2 (82.50 kg/ha) series accounted for 21% and 42% of the N fertiliser (200 kg/ha). Nevertheless, a meta-analysis of field studies pointed out that biochar would not be expected to replace mineral N fertiliser fully (Ye et al. 2020), as biochar N (mainly in the form of heterocyclic aromatic N) was difficult to use by crops (Knicker 2010). Meanwhile, biochar also had a complex reaction with soil, indirectly increasing nutrient availability for plant uptake (Biederman and Harpole 2013). One of the important reasons was that the soil microbial community was altered by adding biochar, which subsequently elevated N availability (Yang et al. 2024). SOC was increased with more use of C because biochar contained highly stable organic carbon (Pandit et al. 2018). Moreover, added biochar could help bind native SOC with soil minerals and form more mineral-organic complexes, which protected native SOC from being decomposed by microorganisms (Han et al. 2014). The indirect mechanism for soil N was that C addition favoured N retention and lowered N leaching, which was the main reason for raising crop N accumulation, promoting crop yield, and increasing N use efficiency (Seki et al. 2022). Regardless of C treatments, there were consistently increasing trends of SOC, total N, and available N with extra P addition (Table 2). These results followed the general conclusion of meta-analysis (Feng and Zhu 2019, Wang et al. 2022), which summarised that P addition could accelerate the accumulation of soil C and N pools, as photosynthetic C fixation and plant N uptake was promoted by added P, and in turn, enlarged organic carbon input into soils derived from plant residues.

Combined effects of C and P fertilisation on soil P status. The impact of C and P combined on crop production in saline-alkali soil remained controversial. In a low-fertility alkaline soil of Pakistan, Arif et al. (2017) reported that joint incorporation of biochar and P fertilisers caused a synergistic effect on wheat and maize yield, and a disproportionately greater increase in phosphorus use efficiency was recorded. In contrast, based on a pot experiment with saline-alkali soil in the Yellow River Delta, Xu et al. (2016) observed negative interactive effects between biochar and P fertilisation on plant biomass, due to enhanced P sorption and precipitation by biochar application. In our results, the soil available P was not proportionally increased or even lowered with more input of C and P together (particularly under the P_2 series) (Table 2). This antagonistic interaction was supposed to be an important reason for the lack of yield increase in the treatment of C_2P_2.

The biochar exhibited a dual role in soil P availability, as biochar could act as a phosphate adsorbent or a source of available phosphorus (Zhang et al. 2016). Thus, previous studies had presented inconsistent results, depending on biochar types, pyrolysis conditions, application rate, soil properties, and P concentration in soil solution (Ghodszad et al. 2021). The main reason for the negative impact of biochar on soil P availability was suggested as that a large number of positive charges originating from high base cation concentration in biochar freed divalent base cations such as Ca and Mg, which precipitated P ions as Ca or Mg phosphates (Chintala et al. 2014). Chintala et al. (2014) further elaborated that biochar increased P sorption and lowered P availability in calcareous soils, in which the intensity of biochar made by corn stover was 2.5 times higher than that of pine-wood-made biochar. Thus, biochars derived from wider feedstocks should be tested to explore their performance on soil P availability in the study area. Recently, P-modified biochar, which was prepared by loading nanoscale P-containing particles on the surface of biochar, was proven to promote soil quality and simultaneously raise plant productivity in coastal saline-alkali soils, displaying better performance than added biochar or added P alone (Zhang

https://doi.org/10.17221/268/2025-PSE

et al. 2022). This alternative way of combined use of C and P fertiliser urgently needs to be verified in the Yellow River Delta. Overall, the unused P from added fertiliser was ultimately fixed by Ca^{2+}, Mg^{2+}, and Na^{+} in alkaline soils (Zhu et al. 2018). Activating these "legacy P" for sustaining crop yields was crucial to relieving farmers' economic burden and reducing the environmental risk of phosphate loss to the water bodies in the Yellow River Delta.

In summary, within the scope of C and P addition, we found C exerted dominant roles in improving yield and heightening dry matter and nutrient accumulation across two years of results. However, the impact of P and the synergistic interactions of C × P we expected were not found. Although the unfavourable weather conditions depressed maize growth and nutrient accumulation, C addition could alleviate this harmful impact by enhancing greater proportions and contributions of dry matter and nutrient remobilisation from pre-anthesis vegetation organs to grain. From the soil viewpoint, soil characteristics (particularly for *Ks*) were mostly ameliorated by C addition. These plant and soil mechanisms were inferred to ensure crop yield stability under excessive rainfall. More notably, the negative interactions of C × P on soil available P and PAC might contribute to no synergistic impact on crop yield when combined use of C and P. Integrating these results, we argued that C application was beneficial to improving soil properties and subsequently stimulating yield formation, but combined incorporation of this kind of C and P fertiliser we used (especially high-amount addition treatment of C_2P_2) was not recommended in the saline-alkali land. This study provided implications for farmers and policy-makers to sustainably utilise and manage C and P fertiliser in the Yellow River Delta.

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