

Article

Trade-Offs of Soil Quality, Wheat Yield and Nutrient Efficiency Under Long-Term Combined Chemical and Manure Fertilization in Vertisols

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Abstract

Organic fertilization is a key strategy for improving soil structure and fertility in China's Vertisols, yet the trade-offs among soil quality enhancement, grain yield performance, and nutrient use efficiency under different organic amendment regimes remain insufficiently elucidated. Based on a unique 43-year field fertilization experiment, this study systematically evaluated the effects of long-term chemical fertilization (NPK) alone, low-dose (NPKLS) and high-dose straw incorporation (NPKHS), combined chemical fertilizer with cattle manure (NPKCM), and pig manure (NPKPM) fertilization on soil physical, chemical properties, crop yields and plant nutrient utilization efficiency. The results showed that NPKCM and NPKPM significantly improved soil physical properties by reducing soil bulk density, improving soil pore structure, and enhancing soil water retention capacity and saturated hydraulic conductivity. Although long-term manure application led to slight soil salt accumulation, the rate of accumulation remained substantially lower than that associated with commercial organic fertilizers and did not approach the crop salinity damage threshold, suggesting low ecological risk. Compared with NPK treatment, manure amendment effectively counteracted soil acidification induced by prolonged chemical fertilization, while also significantly increasing soil total phosphorus and available phosphorus content, and elevated the proportion of active phosphorus (PAC). The improved soil phosphorus activation capacity and comprehensive soil quality further contributed to substantial increases in wheat grain yield under NPKCM and NPKPM treatments. Despite these agronomic benefits, the additional nitrogen and phosphorus inputs from manure resulted in soil nutrient surpluses, which considerably reduced nitrogen and phosphorus partial factor productivity as well as agronomic efficiency. In contrast, straw incorporation treatments (NPKLS, NPKHS) sustained stable crop yield without notable declines in nutrient efficiency, positioning them as a greener and more sustainable approach to balancing grain production with resource use efficiency. These findings highlight the need to integrate nutrient credits from manure into fertilization program. Given the 43-year evidence, fertilization strategy should consider not only the nutrients supplied by manure but also the quantities exported through harvested products, with adjustments based on annual soil fertility analyses. Such nutrient budgeting is essential to maximize fertilizer use efficiency, prevent excessive phosphorus accumulation, and maintain balanced soil fertility over time.



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Keywords: long-term fertilization; farmyard manure; soil structure; P utilization efficiency; crop yield

1. Introduction

Vertisols, locally known as Shajiang black soils in China, are characterized by low organic matter and nutrient concentrations, accompanied by low and unstable crop yields [1]. In recent years, agricultural production in Vertisol has largely relied on heavy fertilization and intensive tillage management [2,3], which have led to topsoil shallowing, deteriorated soil permeability, and declining soil organic carbon content [4]. Furthermore, the rapid expansion of intensive livestock operations in this region has been accompanied by low manure recycling rates and serious environmental degradation [5,6]. Given that, exploring the scientific combined application of organic and inorganic fertilizers is not only beneficial for improving topsoil structure and enhancing organic carbon sequestration, but also helps reduce chemical fertilizer inputs and promote the recycling of livestock manure resources. Such efforts are therefore of great significance for the green and sustainable development of agriculture.

Organic fertilization is widely recognized as an effective practice for improving both soil fertility and soil structure [7,8], as it supplies substantial organic matter and mineral nutrients, thereby greatly enhancing soil aggregate stability and strengthening soil water and nutrient retention capacity [9,10]. Nevertheless, studies have indicated that the beneficial effects of organic fertilizers or soil amendments on soil structure require a relatively long time to fully manifest [11]. Compared with organic fertilization, balanced mineral fertilization, either applied alone or combined with organic manure, can provide more rapid nutrient supply and intensify microbial mineralization [10,12], which effectively elevates soil organic matter and nutrient pools and optimize soil physical structure [13,14]. Despite these widely reported advantages, recent studies have revealed that organic fertilization introduced large amounts of salts, leading to a graded soil structure as evidenced by the disintegration of soil aggregates [13,15]. However, this structural degradation is currently only evident at the microscopic aggregate scale. Whether it will affect the soil aeration and water-holding capacity at larger scales still remains unclear [15–17]. Elucidating this cross-scale relationship is crucial for establishing a reasonable fertilization regime, as the disruption of aggregates does not necessarily imply a disruption in macroporosity continuity.

In addition to the effects on the soil structure, organic fertilizers contain considerable mineral nutrients, which can be mineralized by microorganisms, releasing mineral nutrients for promoting crop growth [18,19]. The sustained input of alkaline cations also enhances soil buffering capacity and neutralizes exchangeable acidity [20], thereby regulating soil acidity and nitrogen/phosphorus availability and improving nutrient use efficiency by reducing nitrogen leaching and phosphorus fixation [21]. Appropriate fertilization strategies can not only increase crop nutrient utilization efficiency, but also mitigate environmental risks such as eutrophication or nutrient leaching [3]. Commercial organic fertilizers are widely used by farmers because of their easy availability and convenience [22]. However, studies have indicated that organic fertilizer application introduced large amounts of salts, leading to an aggravating soil salt stress on crops as the years of application increased [23,24]. Compared with the commercial organic fertilizer, farmyard manure application was also reported result in aggregate dispersion and increased risk of nutrient leaching due to excessive nutrient input [3,15]. Nevertheless, the risk of salt damage to crop growth and the efficiency of crop utilization under long-term manure application has not yet been assessed.

To date, the positive impact of organic fertilization on production has been widely reported. However, the long-term effects of fertilization on soil structure and their residual nutrient effects on crops remain inadequately evaluated. Given the increased risks of environmental pollution and soil structure degradation, the objective of this study were to (1) assess the overall effects of applying farmyard manure to soil properties, crop yields, and nutrient use efficiency and to (2) identify the key factors affecting crop growth and the underlying mechanisms by integrating soil physical quality, nutrient utilization and crop productivity based on a unique 43-year long-term fertilization experiment. We hypothesized that applying manure in combination with chemical fertilizers may reduce the risk of soil salt accumulation and increase crop yields by improving nutrient retention.

2. Materials and Methods

2.1. Experimental Design

The experimental site is located at the long-term fertilization experimental station on Shajiang black soil, Ministry of Agriculture, in Mengcheng County, Anhui Province (33°13' N, 116°37' E), which was established in 1982. The region has a warm temperate, semi-humid monsoon climate, with an annual mean temperature of 14.8 °C and an average annual precipitation of 900 mm. The soil, developed from fluvio-lacustrine sediments, is classified as Vertisol [25], with the sand content of 280 g·kg⁻¹, silt 306 g·kg⁻¹ and clay content of 414 g·kg⁻¹, respectively. The initial physicochemical properties of the topsoil (0–20 cm) were as follows: bulk density 1.45 g·cm⁻³, pH 7.4, organic carbon 10.4 g·kg⁻¹, total nitrogen 0.96 g·kg⁻¹, total phosphorus 0.28 g·kg⁻¹, available nitrogen 84.5 mg·kg⁻¹, available phosphorus 9.8 mg·kg⁻¹, and available potassium 125 mg·kg⁻¹. The cropping system is a wheat–soybean rotation.

The experiment contains six treatments (Table 1): no fertilizer (CK), chemical fertilizer alone (NPK), chemical fertilizer plus low-rate wheat straw (NPKLS), chemical fertilizer plus high-rate wheat straw (NPKHS), chemical fertilizer plus cattle manure (NPKCM), and chemical fertilizer plus pig manure (NPKPM). Each treatment was replicated four times, with individual plot sizes of 75 m² (15 m × 5 m). The application rates of N, P, and K were 180, 90, and 135 kg·ha⁻¹, respectively. For organic amendments, the low and high wheat straw rates were 3750 kg·ha⁻¹ and 7500 kg·ha⁻¹, respectively (the straw contained, on a dry weight basis, 482 g C, 5.5 g N, 1.2 g P, and 11.5 g K per kg); fresh cattle manure was applied at 30,000 kg·ha⁻¹ (dry-basis contents: 374 g C, 8.0 g N, 4.0 g P, and 4.0 g K per kg); and fresh pig manure was applied at 15,000 kg·ha⁻¹ (dry-basis contents: 366 g C, 17 g N, 9.0 g P, and 9.0 g K per kg). The total annual N, P, K, C inputs and C:N ratio for each treatment were shown in Table 1. All inorganic fertilizers and organic materials were applied once each year before wheat sowing in October, which were thoroughly mixed into the soil before manual tillage (12–15 cm). The fertilization rates for each treatment are presented in Table 1. Both wheat and soybean cultivars were locally dominant varieties. Wheat was sown at 187.5 kg·hm⁻² by hand drilling with a row spacing of 25 cm; soybean was sown at 75 kg·hm⁻² by hand dibbling, also with a row spacing of 25 cm. All field management remained consistent since the experiment began.

2.2. Soil Sampling and Determination

After wheat harvest in 30 May 2025, undisturbed soil samples were collected from the 0–20 cm and 20–40 cm layers using PVC cylindrical samplers (100 cm³). The core samples were used to determine soil bulk density and saturated hydraulic conductivity. Mixed disturbed soil samples were also collected from five random points in each plot at a depth of 0–20 cm and 20–40 cm to measure soil nutrient contents, pH, electrical conductivity (EC_{1:1}, soil:water ratio 1:1), and aggregate stability.

Table 1. Application rates of fertilizer under different treatments ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$). CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure.

Period	Treatment	Chemical Fertilizer ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)				Organic Amendment ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)				Total Input ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)				
		N	P	K	Amount (Fresh Base)	Amount (Dry Base)	C Input	N Input	P Input	K Input	N Input	P Input	K Input	C:N
1983–2006	CK	0	0	0	0	0	0	0	0	0	0	0	0	/
	NPK	180	39.3	112	0	0	0	0	0	0	180	39.3	112	0.0
	NPKLS	180	39.3	112	3750	2512.5	1211	13.8	3.0	28.9	193.8	42.3	140.9	6.2
	NPKHS	180	39.3	112	7500	5025	2422	27.6	6.0	57.8	207.6	45.3	169.8	11.7
	NPKCM	180	39.3	112	30,000	12,000	4488	96.0	48.0	48.0	276	87.3	160	16.3
	NPKPM	180	39.3	112	15,000	45,000	1647	76.5	40.5	40.5	256.5	79.8	152.5	6.4
2007–2011	CK	0	0	0	0	0	0	0	0	0	0	0	0	/
	NPK	180	39.3	112	0	0	0	0	0	0	180	39.3	112	0
	NPKLS	180	39.3	112	3750	2512.5	1211	13.8	2.8	28.9	193.8	42.1	140.9	6.2
	NPKHS	180	39.3	112	7500	5025	2422	27.6	5.5	57.8	207.6	44.8	169.8	11.7
	NPKCM	180	39.3	112	30,000	12,000	4488	96.0	48.0	48.0	276	87.3	160	16.3
	NPKPM	180	39.3	112	15,000	45,000	1647	76.5	63.9	40.5	256.5	103.2	152.5	6.4

Phosphorus fractions included water-extractable phosphorus ($\text{H}_2\text{O-P}$), NaHCO_3 -extractable inorganic and organic phosphorus ($\text{NaHCO}_3\text{-Pi}$ and $\text{NaHCO}_3\text{-Po}$), NaOH -extractable inorganic and organic phosphorus (NaOH-Pi and NaOH-Po), dilute HCl -extractable inorganic phosphorus (HCl-P), and residual phosphorus (Residual-P) were determined by using the Hedley method [26]. At wheat harvest, all wheat plants from each plot were harvested, air-dried, threshed, and grain yield was determined.

2.3. CT Scanning and Image Analysis

Undisturbed core samples were first water equilibrated at the matric potential of -10 kPa in a sand box to maintain consistent moisture status, then they were scanned by using an industrial X-ray computed tomography (CT) scanner (phoenix v|tome|x S 240, Nikon Metrology, Wunstorf, Germany) to quantify soil pore characteristics. The scanning voltage was 160 kV and current was 170 mA, with a resolution of $50\text{ }\mu\text{m}$. Image analyses were performed using Fiji (Image J) software (version 2.16.0). First, the grayscale images were denoised by using the “non-local means denoising” tool, followed by the application of an “unsharp mask” to enhance local contrast. A representative region of interest (ROI) with a diameter of 2.65 cm and a height of 4.0 cm was extracted from the center of each CT volume to avoid edge artifacts. The images were then segmented into macropores and backgrounds with the thresholds determined through visual inspection.

Several structure metrics of image-based macropores, like porosity, Euler number, tortuosity, pore size distribution and porosity distribution along with depth were quantified. Macroporosity was calculated as the percentage of macropore voxels relative to the total voxels within the ROI. Mean pore diameter ($\bar{\phi}$) and pore size distribution were derived using the maximum inscribed sphere method implemented via the “local thickness” tool. Pore sizes were categorized into four diameter classes: $<30\text{ }\mu\text{m}$ $\bar{\phi}$, $30\text{--}200\text{ }\mu\text{m}$ $\bar{\phi}$, $200\text{--}500\text{ }\mu\text{m}$ $\bar{\phi}$, and $>500\text{ }\mu\text{m}$ $\bar{\phi}$. Porosity for pores $<30\text{ }\mu\text{m}$ was calculated as the difference between the oven-dried total porosity and image-based macroporosity. The Euler number, used as an indicator of local pore connectivity, was measured using the “Bone J” plugin. More negative values indicate better connected pore networks. Geometric tortuosity between two points was defined as the ratio of the effective pore path length to the straight-line distance between them. Global tortuosity was obtained by averaging the tortuosity values of all individual pore branches, where each branch corresponds to a continuous line of connected voxels. The macroporosity along with depth were determined by analyzing particles.

2.4. Statistical and Data Analysis

Statistical analyses were conducted in IBM SPSS 22.0 (SPSS Inc., Chicago, IL, USA). Data were first tested for normality (Shapiro–Wilk test) and homogeneity of variance (Levene’s test), with variables violating these assumptions that were log-transformed before analysis. Two-way analysis of variance (ANOVA, at $p < 0.05$) was conducted to assess the effects of different treatments on the soil physiochemical properties and crop yield. Fisher’s least significant difference (LSD) method was used for the multiple comparisons of means. To evaluate the relative contributions of soil indicators to crop yield, a random forest (RF) model was employed using the “A3” and “rfPermute” packages in R software; a predictor was considered strong if its p value was <0.05 and its explained variance was >0 . The random forest model was constructed using 500 trees ($n_{tree} = 500$), and the number of variables randomly selected at each node split was set as $m_{try} = 3$. Spearman’s correlation analysis was conducted to explore the relationships between key soil properties and crop yield in 2025. Partial least squares structural equation modeling (PLS-SEM) was constructed using SmartPLS 4 to disentangle the direct and indirect pathways through which fertilization management practices affect crop yield. Model convergent validity was assessed via average variance extracted (AVE) and composite reliability (CR), with all constructs meeting the recommended thresholds ($AVE > 0.50$, $CR > 0.70$). Discriminant validity was confirmed using both the Fornell–Larcker criterion and the heterotrait–monotrait (HTMT) ratio (<0.85). The model fit was evaluated using the standardized root mean square residual (SRMR), which was directly obtained from SmartPLS 4 output and yielded a value of 0.065 (<0.08), indicating an acceptable fit.

3. Results

3.1. Soil Physical Properties Under Long-Term Manure Fertilization

Organic fertilization exerted significant effects on soil physical properties (Table 2). Relative to the CK treatment, all fertilized treatments significantly reduced soil bulk density (ρ_b) in the 0–20 cm layer and increased saturated hydraulic conductivity (K_s) by six- to 13-fold in the 20–40 cm. Long-term application of cattle manure (NPKCM) and pig manure (NPKPM) also markedly decreased ρ_b by 4.3–10.3% and increased soil field capacity (θ_{FC}) by 8.3–24.2% compared to the NPK treatment. Among all organic-amended treatments, NPKCM exhibited the lowest ρ_b and the highest θ_{FC} , whereas NPKPM yielded the greatest K_s . Despite these improved soil physical properties, the mean weight diameter (MWD) of aggregates were significantly greater in all fertilized treatments than in CK ($p < 0.05$).

3.2. Soil Pore Characteristics Under Long-Term Manure Fertilization

Long-term organic fertilization regimes exert differential effects on soil pore structure (Figure 1, Table 3). In the 0–20 cm layer, macroporosity generally followed the order: NPKCM, NPKPM, NPKHS, NPKLS $>$ NPK $>$ CK. Among the organic-amended treatments, manure application (NPKCM and NPKPM) treatment exerted a significantly greater improvement effect on soil pores compared with straw incorporation, with NPKPM treatment exhibited the highest macroporosity.

Regarding pore connectivity, only the NPKCM treatment exhibited a significant increase relative to CK and NPK among all organic amendments, whereas NPKLS, NPKHS, and NPKPM showed markedly lower connectivity. Soil pore tortuosity followed the order: NPKCM, NPKPM, NPKHS, NPKLS $>$ CK $>$ NPK, with manure amendments exerting a stronger promoting effect on tortuosity than straw incorporation.

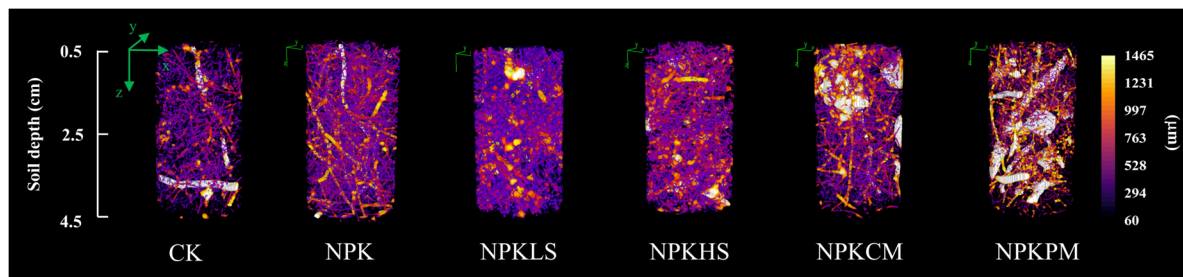


Figure 1. Soil macropores obtained through X-ray CT scanning under different fertilization treatments. CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure.

Table 2. Soil physical properties under different fertilization regime in the 0–40 cm soil layer. CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure. ρ_b , θ_{FC} , K_s , MWD indicate soil bulk density, soil field capacity, soil saturated water conductivity, and mean weight diameter of soil aggregates, respectively. Different lower cases indicate significant differences among fertilization regime under the same soil depth ($p < 0.05$). ** means much significant difference ($p < 0.01$). The freedom of treatment, depth, treatment and depth coupling are 5, 1 and 5, respectively—the same as below.

Depth (cm)	Treatment	ρ_b (g·cm ⁻³)	θ_{FC} (cm ³ ·cm ⁻³)	K_s (mm·min ⁻¹)	MWD (mm)
0–20	CK	1.26 ± 0.01 a	0.274 ± 0.01 c	0.820 ± 0.10 c	8.40 ± 0.69 d
	NPK	1.16 ± 0.02 ab	0.277 ± 0.01 c	0.808 ± 0.03 c	10.1 ± 0.38 cd
	NPKLS	1.09 ± 0.02 b	0.268 ± 0.01 c	0.407 ± 0.05 d	11.8 ± 0.87 bc
	NPKHS	1.09 ± 0.02 b	0.300 ± 0.01 b	0.392 ± 0.03 d	13.7 ± 0.52 a
	NPKCM	1.04 ± 0.07 b	0.344 ± 0.01 a	1.04 ± 0.04 b	11.9 ± 0.72 ab
	NPKPM	1.11 ± 0.02 b	0.320 ± 0.01 ab	1.27 ± 0.06 a	10.6 ± 0.15 c
20–40	CK	1.43 ± 0.05 a	0.359 ± 0.02 a	0.034 ± 0.01 d	7.48 ± 0.58 a
	NPK	1.47 ± 0.04 a	0.273 ± 0.01 b	0.383 ± 0.01 ab	8.44 ± 0.27 a
	NPKLS	1.46 ± 0.02 a	0.284 ± 0.02 b	0.349 ± 0.04 b	8.99 ± 0.35 a
	NPKHS	1.53 ± 0.02 a	0.276 ± 0.01 b	0.338 ± 0.03 bc	8.63 ± 1.08 a
	NPKCM	1.46 ± 0.06 a	0.301 ± 0.02 b	0.237 ± 0.06 c	7.88 ± 0.78 a
	NPKPM	1.44 ± 0.03 a	0.313 ± 0.003 ab	0.470 ± 0.03 a	7.93 ± 0.34 a
<i>p</i> value of significance					
Treatment		0.185	0.01 **	0.001 **	0.001 **
Depth		0.001 **	0.501	0.001 **	0.001 **
Treatment × depth		0.007 **	0.002 **	0.001 **	0.023 **

Table 3. Soil pore characteristic parameters in the 0–20 cm layer based on CT images. CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure.

Treatment	Macroporosity %	Pore Size Distribution				Euler Number	Tortuosity
		<50 μm	50–200 μm	200–500 μm	>500 μm		
CK	0.058 ± 0.008 d	0.313 ± 0.008 b	0.002 ± 0.001 e	0.05 ± 0.002 b	0.03 ± 0.008 c	−6333 ± 275 b	1.278 ± 0.005 b
NPK	0.124 ± 0.006 c	0.342 ± 0.005 a	0.015 ± 0.002 c	0.03 ± 0.008 b	0.02 ± 0.010 c	−16,968 ± 600 b	1.234 ± 0.001 c
NPKLS	0.195 ± 0.001 b	0.346 ± 0.010 a	0.009 ± 0.001 d	0.03 ± 0.004 b	0.03 ± 0.002 c	−1973 ± 148 d	1.293 ± 0.003 a
NPKHS	0.093 ± 0.005 c	0.282 ± 0.012 b	0.023 ± 0.004 b	0.10 ± 0.005 a	0.07 ± 0.003 b	−8803 ± 859 c	1.299 ± 0.004 b
NPKCM	0.197 ± 0.020 b	0.295 ± 0.004 b	0.012 ± 0.003 c	0.09 ± 0.006 a	0.12 ± 0.005 a	−29,885 ± 3993 a	1.299 ± 0.003 a
NPKPM	0.353 ± 0.024 a	0.259 ± 0.010 c	0.035 ± 0.004 a	0.08 ± 0.003 a	0.06 ± 0.005 b	−1215 ± 119 d	1.291 ± 0.001 a

Different lower letters indicate significant differences among treatments.

3.3. Soil Physical Properties Under Tillage Practices

Among all fertilized treatments, SOC and nutrient contents generally ranked in the order: NPKCM, NPKPM > NPKHS, NPKLS > NPK > CK. The NPKCM treatment exhibited the highest SOC and TN in the 0–20 cm layer, while TP, AN and AP was shown under the NPKPM treatment within this layer. In the 20–40 cm layer, NPKPM had the greatest SOC and soil nutrient concentrations.

Soil $EC_{1:1}$ and pH was markedly raised by NPKCM, NPKPM relative to CK and NPK treatments. Compared to the NPK, $EC_{1:1}$ under the NPKCM and NPKPM rose by 110.7–121.3% in the 0–20 cm layer and 53.6–63.8% in the 20–40 cm layer. Relative to the initial $EC_{1:1}$ values ($0.30 \text{ dS}\cdot\text{m}^{-1}$ for 0–20 cm and $0.28 \text{ dS}\cdot\text{m}^{-1}$ for 20–40 cm) measured at the beginning of the trial, the annual increment of $EC_{1:1}$ reached approximately $0.007\text{--}0.017 \text{ dS}\cdot\text{m}^{-1}$ (0–20 cm) and $0.003\text{--}0.011 \text{ dS}\cdot\text{m}^{-1}$ (20–40 cm) after 43 years of continuous manure incorporation. Soil pH under NPKCM and NPKPM was significantly enhanced by 11.3–22.2% (0–20 cm) and 11.3–17.9% (20–40 cm) compared with NPK ($p < 0.05$).

In addition to improving soil pore structure and water infiltration capacity, manure amendments also effectively alleviated soil acidification. However, soil mean weight diameter (MWD) showed a decreasing trend with increasing $EC_{1:1}$.

3.4. Crop Yield and Under Long-Term Manure Fertilization

Crop yield is strongly correlated with fertilization management (Figure 2). Among organic amendment treatments, NPKCM and NPKPM produced greater yield increases than NPKHS and NPKLS treatments. Compared with the NPK alone, the NPKCM and NPKPM significantly increased wheat yield by 13.7% and 13.9%, respectively ($p < 0.05$). Based on the random forest model, the proportion of labile phosphorus (PAC) and soil organic carbon (SOC) concentration were identified as the key soil factors regulating wheat yield ($p < 0.01$), followed by total phosphorus (TP) and total nitrogen (TN) (Figure 3, $p < 0.05$).

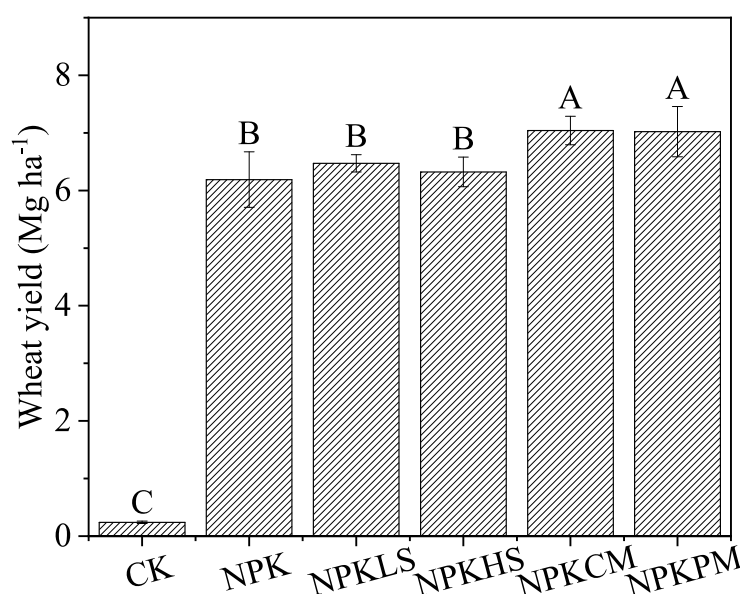


Figure 2. Wheat yield under different fertilization regimes. CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure. Different letters indicate significant differences among treatments.

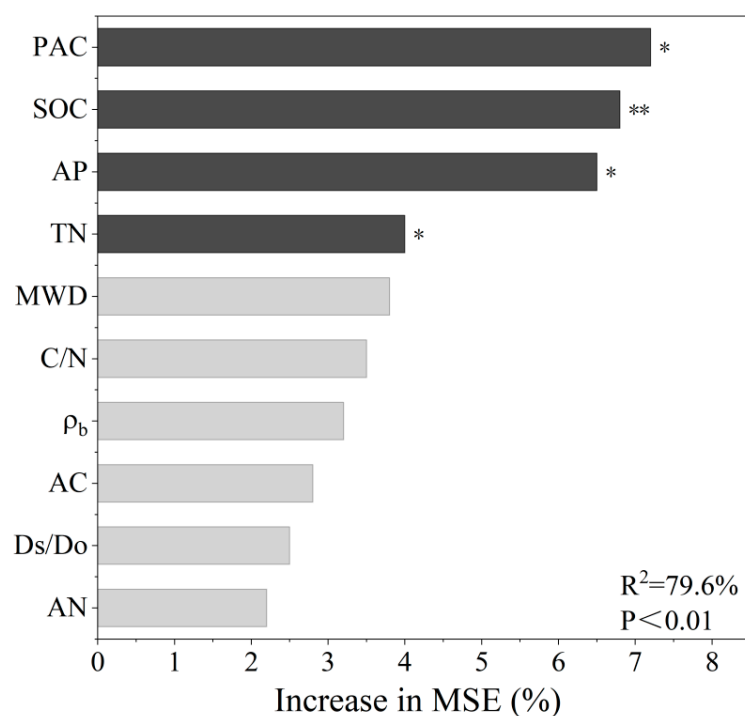


Figure 3. Driving factors for wheat yield by using random forest analysis. Percentage increases in MSE (mean squared error) of variables were used to estimate the importance of these predictors, and higher MSE% values imply greater importance of predictors. *, $p < 0.05$; **, $p < 0.01$.

3.5. Soil Phosphorus Under Long-Term Manure Fertilization

Fertilization regimes significantly affected the concentrations and proportional of soil labile phosphorus (labile P), moderately labile phosphorus (moderately labile P), and non-labile phosphorus (non-labile P) (Figures 4 and 5; $p < 0.05$). Compared to the NPK treatment, NPKCM and NPKPM significantly increased labile P concentrations by 270.4–534.8% and 638.1–1874.1%, respectively, and elevated moderately labile P by 46.1–93.5% and 202.0–405.6%, respectively. In terms of the percentage proportions of each phosphorus fraction across the 0–40 cm soil layer, NPKPM exhibited the highest proportions of labile P and moderately labile P, along with the lowest proportion of non-labile P, among all fertilization treatments ($p < 0.05$).

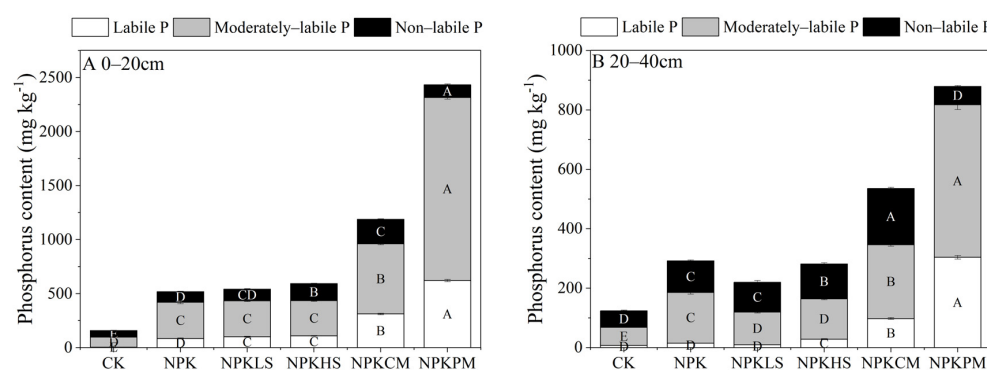


Figure 4. Effects of different fertilization methods on the distribution of phosphorus fractions (labile P, moderately labile P and non-labile P). CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure. The different letters indicate significant differences among treatments.

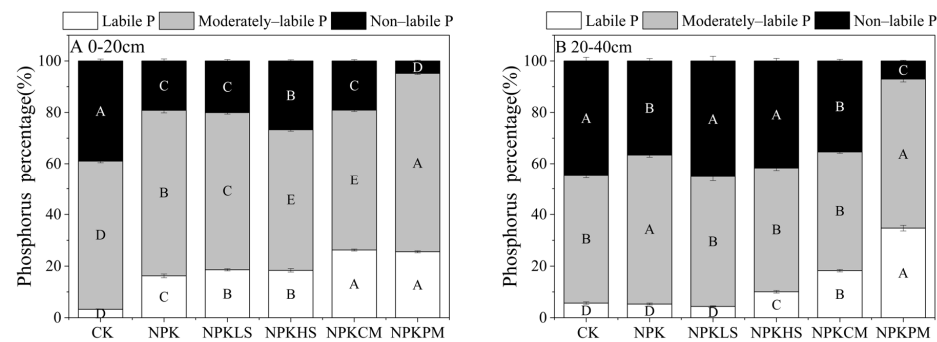


Figure 5. Effects of different fertilization methods on the percentages of soil phosphorus fractions (labile P, moderately labile P, and non-labile P). CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure. The different letters indicate significant differences among treatments.

3.6. Contribution of Soil Properties to Crop Yield Under Long-Term Manure Fertilization

Partial least squares structural equation modeling (PLS-SEM) analysis were shown in Figure 6. Across all fertilization treatments, phosphorus input significantly increased the concentration and proportion of moderately labile P (path coefficient $\beta = 0.614$, $p < 0.01$), and exerted a strong positive effect on the transformation from moderately labile P to labile P ($\beta = 0.744$, $p < 0.01$). Labile P markedly elevated soil available phosphorus content ($\beta = 1.655$, $p < 0.01$), which in turn positively contributed to crop yield ($\beta = 0.954$, $p < 0.01$). Despite soil pH had a significant negative effect on yield formation ($\beta = -0.700$, $p < 0.01$), the increased pH under NPKCM and NPKPM accelerated the conversion of moderately labile P into labile P, thereby raising the concentration and proportion of labile P and improving overall soil phosphorus availability, which ultimately contributed in higher crop yields.

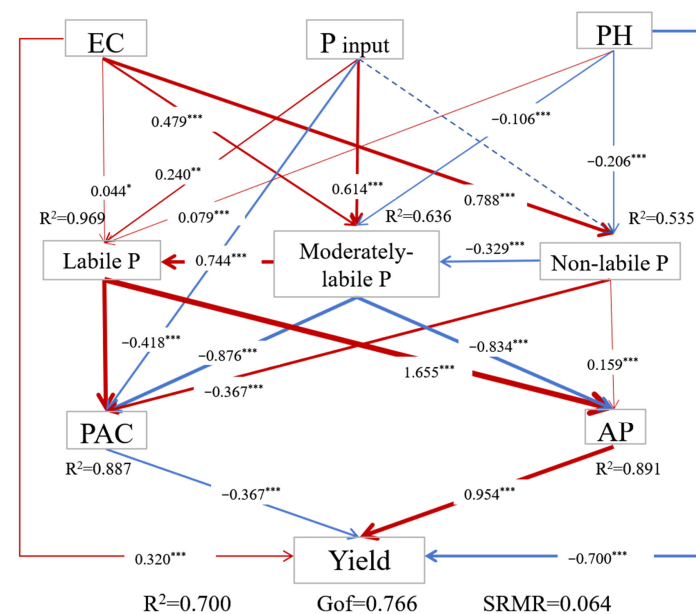


Figure 6. Partial least squares structural equation model (PLS-SEM) reveals the direct and indirect effects of phosphorus input rate, EC, pH, labile P, moderately labile P, non-labile P, PAC, and AP on wheat yield under different fertilization treatments. The red and blue arrows depict positive and negative correlations, respectively. The numbers along the arrow lines and the arrow thickness represent the standardized path coefficients. Dashed arrows indicate non-significant relationships. R^2 refers to the coefficient of determination. The GoF index reflects the model's goodness of fit. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

3.7. Partial Factor Productivity and Agronomic Efficiency of Nitrogen and Phosphorus Under Long-Term Manure Fertilization

The partial factor productivity and agronomic efficiency of both soil nitrogen and phosphorus declined with organic material addition, following as: NPK > NPKLS > NPKHS > NPKCM > NPKPM (Figure 7). Compared with the NPK treatment, NPKCM and NPKPM reduced nitrogen partial factor productivity by 15% and 19%, and significantly decreased nitrogen agronomic efficiency by 14–18%. Meanwhile, phosphorus partial factor productivity was significantly lowered by 50% and 55%, with an identical 50% and 55% reduction observed in phosphorus agronomic efficiency.

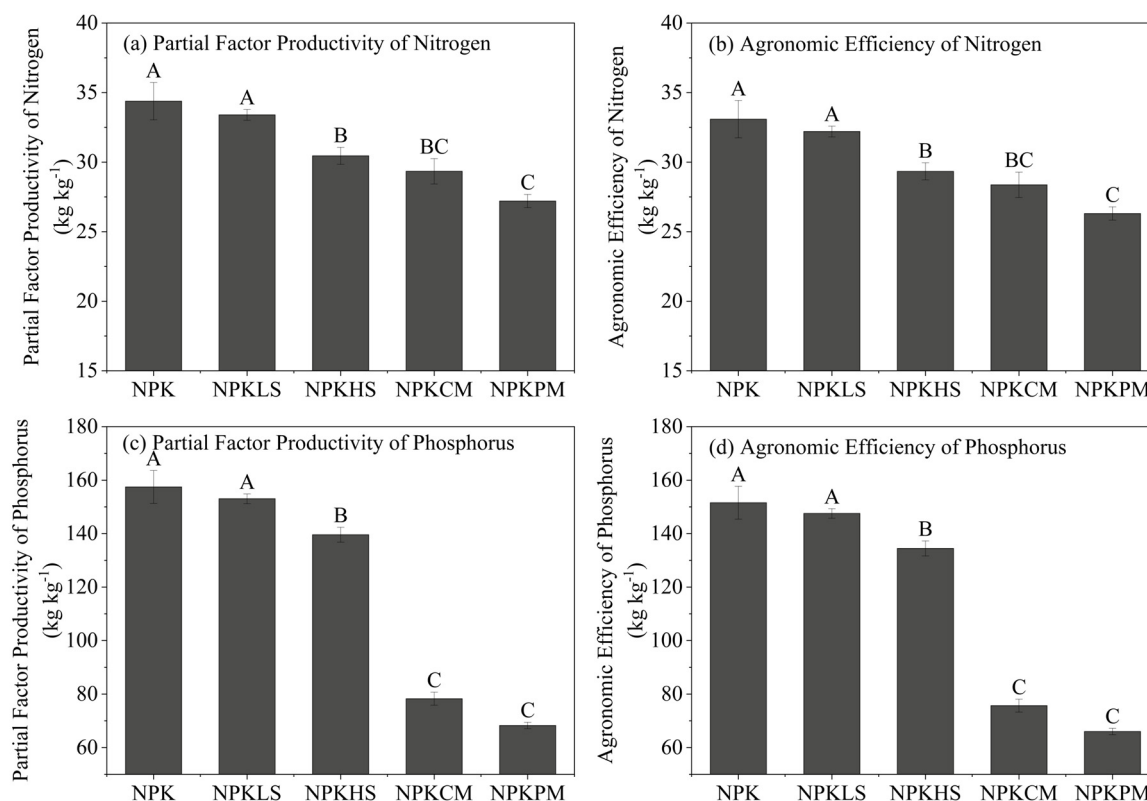


Figure 7. Partial factor productivity and agronomic efficiency of nitrogen and phosphorus under different fertilization treatments. CK, NPK, NPKLS, NPKHS, NPKCM, NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure. The different letters indicate significant differences among treatments.

4. Discussion

4.1. Effect of Long-Term Manure Fertilization on Soil Physical Properties

Fertilization treatments exerted significant influences on soil physical structure (Table 2). The investigated Vertisol is characterized by a heavy clay texture with strong shrink–swell properties, and high soil bulk density (ρ_b) has long been identified as a core limiting factor for root proliferation, nutrient absorption and crop productivity in this soil type [27]. Compared with the NPK alone, long-term organic fertilization significantly reduced ρ_b by 4.3–10.3% in the 0–20 cm layer ($p < 0.05$), with the greatest reduction observed in the NPKCM treatment. Associated with the decrease in ρ_b , organic amendment treatments also substantially optimized soil pore structure (Figure 1), with NPKCM and NPKPM treatments achieving the most highest macroporosity and macro-pore connectivity, followed by NPKHS and NPKLS treatments (Table 3). These improvements in soil structure likely originated from physical dilution and the biological regulation processes induced

by exogenous organic matter input. Under long-term organic amendment incorporation, the loose, porous structure of organic materials directly dilutes dense clay particles and loosens soil structure. Furthermore, as reported in numerous studies, continuous organic carbon input sustains high soil microbial activity, which accelerates organic decomposition and humification and thereby increases the inter-aggregates macroporosity and their connectivity [28–30]. Hargreaves et al. [31] also reported that manure notably increased pores ranging from 10 to 20 μm . Accordingly, the observed reductions in ρ_b and increases in macroporosity may be attributed to a combination of direct physical effects (e.g., dilution and structural loosening by organic particles) and potential microbial-mediated aggregation processes. For the investigated Vertisol, the strong shrink–swell capacity exerts strong physical remolding on pore architecture [1]. Such structural elasticity may sometimes overwhelm the biological effects of organic inputs as soil wetting and drying [25,27]. Nevertheless, the water potential equilibrium of -10 kPa in this study did not cause significant shrinkage and swelling. Therefore, the favorable pore structure should be attributed to biophysical processes under long-term organic matter application.

The poor soil water and air supply capacity caused by the compact clayey structure is the primary constraint limiting nutrient activation and crop yield formation in this regional farmland [27,32,33]. In this study, θ_{FC} peaked under manure-amended treatments, followed by straw incorporation and NPK treatment. The increased θ_{FC} under NPKCM and NPKPM treatments indicated an enhanced soil water retention under manure-amended treatments, which may be attributed to the increased micropores under organic fertilization as many studies reported. Micropores are typically formed during organic-induced aggregate formation, which can effectively store soil capillary water, improving soil water holding capacity and stabilizing soil water supply for crop growth throughout the growing season [10,28]. Besides water retention properties, saturated hydraulic conductivity (K_s) is also strongly controlled by pore size distribution and connectivity [34]. Compared with NPK, the greater pore volume and enhanced pore connectivity under manure amendments significantly raised K_s by 28.7–57.2%. This improved water percolating capacity may also promoted the downward migration of soluble nutrients and organic compounds, thereby increasing soil nutrient content in the 20–40 cm (Table 4). These structural optimizations endow the Vertisol with excellent drainage and aeration recovery capacity, which helps prevent surface waterlogging and root hypoxia under heavy rainfall, maintains efficient root respiration and nutrient uptake, and indirectly improves fertilizer use efficiency by reducing water and nutrient leaching loss.

Despite the marked improvements in soil physical structure and hydrological functions, MWD under NPKCM and NPKPM were lower compared to the straw-amended treatments (Table 2, $p < 0.05$). This results was consistent with previous studies [13,18]. Despite organic manure is rich in organic matter and good ability in binding clay minerals to form soil aggregates [35,36], modern livestock breeding commonly uses high-salinity feed additives, leading to slight salt accumulation in long-term manure-amended soil. The accumulated soluble salts therefore slightly disperse soil micro-aggregates and weaken aggregate stability, ultimately reducing soil MWD [5].

4.2. Effect of Long-Term Manure Fertilization on Soil Chemical Properties

We previously found that long-term application of commercial organic fertilizers carries a high salinity risk in soil [20]. Based on this 43-year field experiment, traditional farmyard manure also lead to salt accumulation. However, compared with 8-year commercial organic fertilization [20], the salt accumulation rate ($0.007\text{--}0.017$ $\text{dS}\cdot\text{m}^{-1}$ year^{-1}) accounted for merely 2.8–27.6% of that under commercial organic fertilization. The salt content after 43-year fertilization did not reached the threshold ($2.5\text{--}3.5$ dS m^{-1}) for crop

salt damage either [37]. This indicated cattle and pig manure markedly slow soil salt accumulation and carry a lower risk of salt damage to crops relative to the commercial organic fertilizers.

Table 4. Soil chemical properties under fertilization treatments in the 0–40 cm soil layer in the wheat harvest period. CK, NPK, NPKLS, NPKHS, NPKCM, and NPKPM indicated chemical fertilizer alone, chemical fertilizer plus low-rate wheat straw, chemical fertilizer plus high-rate wheat straw, chemical fertilizer plus cattle manure, and chemical fertilizer plus pig manure. SOC, TN, TP, AN, AP, PAC, EC_{1:1}, indicate soil organic carbon content, total nitrogen, total phosphorus, available nitrogen, available phosphorus, proportion of available phosphorus and soil electric conductivity under soil–water ratio of 1:1. The different letters indicate significant differences among treatments. *, $p < 0.05$; **, $p < 0.01$.

Depth (cm)	Treatment	SOC (g·kg ⁻¹)	TN (g·kg ⁻¹)	TP (g·kg ⁻¹)	AN (mg·kg ⁻¹)	AP (mg·kg ⁻¹)	PAC (%)	EC _{1:1} (dS·m ⁻¹)	pH
0–20	CK	5.33 ± 0.37 e	1.20 ± 0.04 e	0.251 ± 0.01 d	70.0 ± 0.01 b	2.25 ± 0.38 d	2.81 ± 0.47 d	0.30 ± 0.02 d	6.84 ± 0.09 a
	NPK	8.76 ± 0.31 b	1.57 ± 0.02 c	0.413 ± 0.02 c	79.3 ± 8.33 b	9.30 ± 0.36 c	11.6 ± 0.44 c	0.47 ± 0.02 cd	5.64 ± 0.14 b
	NPKLS	11.6 ± 0.48 c	1.66 ± 0.04 c	0.462 ± 0.01 c	91.0 ± 5.72 b	10.7 ± 0.36 c	13.4 ± 0.26 c	0.29 ± 0.01 d	5.55 ± 0.09 b
	NPKHS	12.4 ± 0.49 c	1.37 ± 0.01 d	0.467 ± 0.01 c	96.3 ± 11.1 b	12.7 ± 0.34 c	15.9 ± 0.42 c	0.55 ± 0.04 bc	5.41 ± 0.06 b
	NPKCM	21.5 ± 0.79 a	2.97 ± 0.09 a	1.05 ± 0.01 b	128.3 ± 11.7 a	60.3 ± 1.66 b	75.3 ± 2.27 b	1.04 ± 0.06 a	6.89 ± 0.07 a
	NPKPM	17.3 ± 1.1 b	2.31 ± 0.10 b	1.76 ± 0.06 a	131.5 ± 8.75 a	68.5 ± 3.20 a	88.6 ± 3.74 a	0.77 ± 0.02 b	6.65 ± 0.08 a
20–40	CK	2.69 ± 0.20 b	0.802 ± 0.02 c	0.195 ± 0.01 d	65.3 ± 4.67 a	1.45 ± 0.14 c	1.82 ± 0.17 c	0.28 ± 0.02 c	6.80 ± 0.06 a
	NPK	5.87 ± 0.13 a	1.18 ± 0.02 ab	0.324 ± 0.03 bc	63.0 ± 7.00 a	3.20 ± 0.08 c	4.00 ± 0.09 c	0.28 ± 0.02 c	6.09 ± 0.13 b
	NPKLS	5.40 ± 0.33 a	1.25 ± 0.02 a	0.246 ± 0.01 cd	52.5 ± 10.5 a	3.11 ± 0.11 c	3.89 ± 0.14 c	0.53 ± 0.06 ab	6.06 ± 0.11 b
	NPKHS	5.50 ± 0.35 a	1.05 ± 0.10 b	0.270 ± 0.02 cd	49.0 ± 8.57 a	3.35 ± 0.11 c	4.19 ± 0.13 c	0.29 ± 0.06 c	6.23 ± 0.12 b
	NPKCM	5.32 ± 0.21 a	1.23 ± 0.03 a	0.372 ± 0.01 b	52.5 ± 10.1 a	18.5 ± 0.16 b	23.1 ± 0.20 b	0.59 ± 0.03 a	6.78 ± 0.08 a
	NPKPM	5.38 ± 0.59 a	1.35 ± 0.05 a	0.639 ± 0.02 a	70.0 ± 8.02 a	36.9 ± 2.66 a	46.1 ± 3.32 a	0.43 ± 0.05 b	6.78 ± 0.03 a
<i>p</i> value of significance									
Treatment		0.001 **	0.001 **	0.001 **	0.031 *	0.001 **	0.001 **	0.001 **	0.001 **
Depth		0.001 **	0.001 **	0.001 **	0.001 **	0.001 **	0.001 **	0.001 **	0.001 **
Treatment × depth		0.001 **	0.001 **	0.001 **	0.028 *	0.001 **	0.001 **	0.001 **	0.001 **

Farmyard manure typically acts as a slow-release nutrient pool. Nevertheless, under long-term application conditions, its gradual mineralization sufficiently replenishes soil mineral nutrients [38]. The increased soil salt content under manure fertilization may be related to the elevated concentrations of SOC and soil nutrition content (TN, AN, TP, AP; Table 4). It is worth noting that the fertilization strategy used in this study was to apply organic fertilizer in addition to an equal amount of chemical fertilizer. The addition of organic fertilizer is a major factor in increasing soil nutrient levels and promoting higher crop yields (Figure 3).

Among the key factor driving crop yield, the PAC was the primary factor affecting crop yield. Although both soil TP and AP increased under conditions of exogenous organic fertilizer application (Table 4), the elevated AP-to-TP ratio (PAC) indicated manure application promoted phosphorus activation (Figures 4 and 5). This activation effect is critical for the investigated Vertisol, where low native nitrogen and phosphorus availability has long been recognized as a major constraint to agricultural productivity [28]. The enhanced P mobilization may be linked to manure-induced shifts in soil pH and its cascading effects on P fractions. After 43 years of continuous chemical fertilization, soil pH declined from an initial 6.84 to 5.41–5.64 (Table 4). Such acidification typically exacerbates P fixation by promoting the precipitation of insoluble Fe-P and Al-P complexes [39], thereby limiting both P availability and crop growth [40]. In contrast, the sustained application of manure introduced substantial alkaline cations (e.g., Ca²⁺, Mg²⁺, K⁺), which directly raised soil pH to 6.65–6.89 in the 0–40 cm layer ($p < 0.05$), and enhanced soil buffering capacity and neutralized exchangeable acidity [17]. As soil pH approaches near-neutral conditions, the solubility of Fe/Al-P minerals decreases while that of Ca-P phases increases, collectively shifting the phosphorus equilibrium toward more plant-available forms.

Beyond pH-mediated dissolution, manure-derived organic matter plays a dual role in P chemistry. On one hand, the humic and fulvic acids released during manure decom-

position possess abundant carboxyl and phenolic hydroxyl groups, which can chelate with Fe^{3+} , Al^{3+} , and Ca^{2+} ions, forming organo-metallic complexes. This chelation effectively reduces the concentration of free metal ions available to precipitate with phosphate, thereby suppressing the formation of sparingly soluble P minerals and maintaining a higher solution-phase P concentration. On the other hand, although the phosphorus naturally present in manure tends to chelate with soil humus, increasing the proportion of moderately available and poorly available phosphorus, applying it to the soil not only significantly mitigates soil acidification, but also accelerates the conversion of moderately soluble phosphorus into soluble phosphorus, increasing the absolute concentration of soluble phosphorus and the proportion of soluble phosphorus, that contributed to crop yield (Figure 6). A previous study in the Vertisol soil [41] showed that soil Olsen-P could be directly transformed by labile organic P (LOP). Both LOP content and percentage of total organic P were rendered significantly higher through long-term additional application of pig or cattle manure than by mineral fertilizer or wheat straw alone [41]. Wang et al. [42] found soil calcium phosphate (Ca-P) was also one of direct sources of Olsen-P. The ability to transform Ca-P to Olsen-P was greatly enhanced by application of pig or cattle manure.

4.3. Impact of Long-Term Combined Application of Manure on Wheat Yield

Long-term application of organic manure (NPKCM and NPKPM) substantially elevated crop grain yield relative to NPK and straw incorporation treatments (NPKLS, NPKHS), as evidenced by the significantly higher yield (Figure 2). Although long-term organic matter substitution has been reported to optimize soil pore structure to alleviate soil physical stress [13] and modulates soil microbial activity to enhance crop nutrient utilization [16], the prominent yield promotion of manure application in this study was found largely attributed to its strong improvement on soil phosphorus fertility. This is supported by the fact that the AP and PAC were identified as two dominant soil drivers contributing the largest marginal increase in comprehensive soil quality index (MSE), with statistically significant correlations ($p < 0.05$). Despite superior crop yield performance, long-term manure addition markedly reduced nitrogen and phosphorus partial factor productivity as well as agronomic efficiency compared with straw incorporation treatments and conventional NPK fertilization (Figure 7). The direct cause may lie in the law of diminishing returns. Under the experimental design, where identical rates of chemical N and P were applied across all fertilized plots, the additional organic nutrients (N and P) introduced through manure amendments inevitably increased the total nutrient input without proportional yield gains, thereby diluting nutrient use efficiency. Correspondingly, NPKCM and NPKPM exhibited significantly lower N partial factor productivity, N agronomic efficiency, P partial factor productivity and P agronomic efficiency than NPK and straw incorporation treatments (NPKLS/NPKHS).

Over the four decades of continuous manure input, the Vertisol have been progressively transformed into a substantial phosphorus reservoir, encompassing not only readily available inorganic P but also moderately labile and even stable organic P pools, which was evidenced by the sustained elevation of TP, AP, and the phosphorus activation coefficient (PAC) across 0–40 cm depth (Table 4). This reservoir formation carries profound implications for soil phosphorus cycling, residual fertility, buffering capacity, and the development of so called legacy phosphorus. From a soil P cycling perspective, the legacy pool serves as a buffering reservoir that can sustain crop P requirements for extended periods even if external P inputs are reduced or temporarily ceased. This multi-pool configuration enhances the buffering capacity against temporary deficits in P supply, thereby stabilizing crop yield under variable environmental conditions. Despite these advantages, it also introduces a critical environmental trade-off. As demonstrated by Hua et al. [3] and Yan et al. [43],

the degree of P saturation in manure-treated soils progressively increases with continued over-application, and once the soil's sorption capacity is exceeded, the risk of dissolved P loss via runoff or leaching escalates sharply. Thus, the same legacy P reservoir that underpins long-term fertility also constitutes a potential diffuse pollution source if not managed judiciously.

Compared with NPKCM and NPKPM, straw incorporation treatments (NPKLS, NPKHS) achieved a better balance between crop productivity and nutrient utilization efficiency (Figures 2 and 6). Unlike manure, crop straw contains relatively low readily available N and P, resulting in less excessive nutrient accumulation in the topsoil under equivalent chemical fertilizer inputs [3]. Consequently, straw incorporation avoids severe declines in nitrogen and phosphorus use efficiency but sustaining stable crop production, demonstrating advantages in nutrient resource saving compared with continuous organic manure application. It is worth noting, however, that long-term straw returning to the field has caused a decrease in pH (Table 4), which may have a certain negative impact on phosphorus activation (Figure 5). The PLS-SEM model (Figure 6) further suggested that despite soil pH exert a direct mild chemical stress on crop yield under acidic or sub-optimal pH conditions. This direct suppression was outweighed by a positive indirect effect mediated through P mobilization. Specifically, the pH recovery (or the alleviation of acidification) promoted AP availability, which in turn stimulated yield formation. Accordingly, when evaluating soil acidification impacts on crop production, the direct chemical stress on root growth and the indirect nutrient-activating benefits that pH shifts may bring must be distinguished. The net outcome depends on the initial soil pH, the magnitude of pH change, and the buffering capacity of the specific soil type, all of which are context-dependent. Therefore, future efforts should focus on determining how to apply additional organic fertilizer or soil acidifiers under conditions of straw return to the field. In addition, it warrants further exploration to identify the threshold level of accumulated nutrient reserves required to reduce external inputs without compromising yield.

5. Conclusions

Based on 43-year fertilization experiment, long-term manure application (NPKCM, NPKPM) was found effectively improved soil structure, increasing SOC and soil nutrient levels. Compared to NPK and straw incorporation treatments (NPKLS, NPKHS), long-term manure application also alleviated soil acidification, increased soil available phosphorus content and active phosphorus proportion, thereby enhancing soil phosphorus supply capacity for crops. Regular monitoring of soil chemistry is also necessary to prevent a sustained increase in pH or nutrient imbalances caused by long-term application. Although manure application led to salt accumulation and decreased aggregate stability, the salt accumulation rate was significantly lower than commercial organic fertilization. The salt content has not reached the threshold for crop salt damage, indicating that salinization is not currently a limiting factor under the conditions evaluated. Despite these advantages, additional nitrogen and phosphorus introduced by manure resulted in nutrient surplus in soil, leading to reduced nitrogen and phosphorus partial factor productivity and agronomic efficiency. Compared to manure amendment, long-term straw incorporation (NPKLS and NPKHS) maintained stable crop yield without obvious nutrient efficiency decline, representing as a green and sustainable approach to achieving a better balance between grain yield and nutrient use efficiency. These findings highlight the need to integrate nutrient credits from manure into fertilization programs. Fertilization strategy should consider not only the nutrients supplied by manure but also the quantities exported through harvested products, with adjustments based on annual soil fertility analyses. Such nutrient

budgeting is essential to maximize fertilizer use efficiency, prevent excessive phosphorus accumulation, and maintain balanced soil fertility over time.

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