

Article

Effects of Replacing Nitrogen Fertilizer with Organic Fertilizer on Soil Physicochemical Properties and Maize Yield in Yunnan's Red Soil

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Abstract

Red soil regions commonly experience land degradation and low nutrient availability. Excessive fertilizer use in recent years has intensified these challenges, necessitating scientifically informed fertilization strategies to ensure agricultural sustainability. To identify optimal fertilization strategies for maize cultivation in Yunnan's red soil regions, this study conducted field experiments involving partial substitution of nitrogen fertilizer with organic manure to determine whether this approach improves soil health and boosts maize yield. Four treatments were compared in a randomized complete block design over one growing season: no fertilization (NF), soil testing and formula fertilization (STF), 15% organic fertilizer (swine manure) replacing nitrogen fertilizer (OF15), and 30% organic fertilizer replacing nitrogen fertilizer (OF30). The results indicated that substituting organic fertilizer for nitrogen fertilizer reduced soil acidification while increasing total phosphorus (TP) and available phosphorus (AP), thereby enhancing soil physicochemical properties. Maize grown under OF30 exhibited improved agronomic traits including plant height, stem diameter, ear height, and ear length. Additionally, the partial replacement of synthetic fertilizer with organic fertilizer notably increased maize yield and the weight of 100 grains, but there was no significant difference ($p < 0.05$) between OF15 and OF30. Moreover, the OF30 treatment generated the highest economic return of 25,981.73 CNY·ha⁻¹. Correlation and principal component analyses revealed that substituting organic fertilizer for nitrogen fertilizer notably influenced total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), and yield, with maize yield positively correlated with TP and AP content. This study presents evidence that replacing 30% of nitrogen fertilizer with organic fertilizer is a viable strategy to enhance soil health, maize productivity, and profitability in Yunnan's red soil regions, providing a crucial scientific foundation to support sustainable agricultural development in the region.

Keywords: organic fertilizer; fertilizer; plateau red soil; sustainable agriculture; economic returns



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1. Introduction

Mineral fertilizers are a key input for intensive crop production systems, yet in Chinese agricultural practices, there is a prevalent tendency to apply excessive amounts of fertilizer

in pursuit of maximizing crop yields. By the end of 2019, China had utilized a total of 54.03 million tons of agricultural fertilizer, surpassing the global average by 5 times [1]. China's fertilizer application exceeds the economic optimum level, leading to diminishing returns and environmental costs [2,3]. While the application of chemical fertilizers has notably boosted crop productivity, prolonged use results in escalated costs, resource depletion, and environmental ramifications such as soil degradation and acidification, which detrimentally impact soil functionality and crop output in the long term [4–7]. Furthermore, China exhibits low efficiency in chemical fertilizer utilization, with plants only being able to absorb 30–40% of the applied nitrogen, leading to over 40% of the administered nitrogen fertilizer being lost to the atmosphere, groundwater, and surface water, contributing to severe surface pollution [8,9]. The effectiveness of applied phosphorus fertilizers is similarly diminished as they are lost through runoff, seepage, or fixation by other soil minerals [10,11]. Consequently, the challenge in agricultural research lies in optimizing fertilizer application to ensure both high and consistent yields.

Several scholars have suggested employing soil testing and formula fertilization technology to tailor fertilization practices to local soil conditions and reduce fertilizer usage [12–14]. While this approach can help mitigate some environmental issues stemming from chemical fertilizers, it does not address all related problems. Organic fertilizers, derived from agricultural organic waste such as crop straw and livestock manure, are rich in organic matter, nitrogen, phosphorus, and potassium [15]. Properly processed organic fertilizers not only offer a solution for managing livestock manure, but also enhance soil microbial environments, supply essential crop nutrients, and elevate agricultural product quality [16–18]. China has a significant amount of organic fertilizer resources, with an annual production of about 5.7 billion tons, mainly derived from livestock manure [19]. However, the utilization rate of organic fertilizers is relatively low, at approximately 40% [20]. Improving the recycling efficiency of organic fertilizers and replacing chemical fertilizers are effective strategies to increase crop yield, preserve fertilizers, and improve efficiency. The impact of replacing chemical fertilizers with organic alternatives on soil properties and crop yields during cultivation has garnered significant attention. Ma et al. [21] demonstrated that substituting 40% of chemical nitrogen with organic fertilizer not only enhances soil nutrient levels and boosts beneficial microorganism populations, but also stabilizes soil pH, leading to a substantial increase in garlic yield. Similarly, Jin et al. [22] and Sun et al. [23] highlighted that partial replacement of chemical fertilizers with organic counterparts can ameliorate soil physicochemical properties, with an optimal replacement ratio enhancing crop yields. Wang et al. [24] observed that utilizing organic fertilizers instead of nitrogen fertilizers enhances soil nitrogen utilization, bacterial and fungal abundance, and nitrogen-related enzyme activity, ultimately increasing rice yields. Shi et al. [25] demonstrated notable enhancements in the agronomic and photosynthetic characteristics of potato plants, including height, stem diameter, chlorophyll levels, and net photosynthetic rate, by replacing chemical fertilizers with organic alternatives. This substitution resulted in improved potato yields and tuber quality. Additionally, Li et al. [26] observed a significantly greater long-term yield enhancement effect from organic fertilizer usage compared to using only chemical fertilizers during a 30-year study period.

Red soil predominates in Yunnan Province, China, covering 30.28% of its cultivated land area and significantly influencing agricultural productivity [27]. This soil type is characterized by acidity, high levels of iron and aluminum oxides, low base saturation, and nutrient deficiencies [28–30]. The excessive use of chemical nitrogen fertilizers over the past three decades has exacerbated soil acidification [31]. Moreover, the acidic nature of red soil leads to strong phosphorus adsorption by iron and aluminum oxides, resulting in limited phosphorus availability, which constrains agricultural productivity in Yunnan's red

soil regions [29,32]. Given these constraints, identifying optimized fertilization strategies is critical. However, the substitution of organic matter for nitrogen fertilizer is uncommon in Yunnan's red soil areas, hindering the adoption of organic fertilization practices. This study focuses on the typical red soil plots in Yunnan Province to investigate how replacing different ratios of nitrogen fertilizer with organic fertilizer impacts soil properties, agronomic characteristics, and maize yield. The aim is to identify an optimal fertilization strategy, explore the most effective combination of organic and inorganic fertilizers, and offer theoretical guidance for scientifically integrating manure into farming practices to enhance the red soil environment and agricultural productivity.

2. Materials and Methods

2.1. Experimental Site

The study was conducted in May 2022 in Tiechi Village (104°23'58" E, 25°82'51" N), Housuo Town, Fuyuan County, Qujing City, in the east of Yunnan Province, China, at an altitude of 1940 m. The area experiences an annual rainfall of approximately 1000 mm and an average annual temperature of 13.5 °C. The soil at the research site is classified as red soil with moderate texture and fertility, with the previous crop being fallow during the winter season. Prior to the experiment, the soil exhibited the following physicochemical properties: pH 5.8, organic matter content 43.7 g·kg⁻¹, total nitrogen content 2.18 g·kg⁻¹, available phosphorus content 73.26 mg·kg⁻¹, and available potassium content 204 mg·kg⁻¹.

2.2. Experiment Design

The field experiment was performed using a completely randomized block design with three replicates. The treatments were as follows: (1) no fertilization (NF), (2) soil testing formula fertilization (STF), (3) organic fertilizer replacing 15% of nitrogen fertilizer (OF15), and (4) organic fertilizer replacing 30% of nitrogen fertilizer (OF30). The application rates and nutrient ratios of N, P₂O₅, and K₂O in the STF treatment were determined through a local fertilization practices survey combined with achievements from soil testing and formulated fertilization [33]. Numerous studies have confirmed that the combined application of organic and chemical fertilizers improves soil health and boosts crop yields, particularly at relatively low substitution rates (around 40%) [25,34–36]. Therefore, based on the STF treatment protocol, we established organic fertilizer substitution ratios for nitrogen in the OF15 and OF30 treatments. P₂O₅ and K₂O inputs were matched to the STF treatment using stoichiometric calculations and adjusted according to the organic fertilizer's P₂O₅ and K₂O content.

Commercial chemical fertilizers including urea (46.40% N), calcium superphosphate (16.00% P₂O₅), and potassium sulfate (50.00% K₂O) were purchased from Yunnan Yunwei Group Co., Ltd., Qujing, China. The organic fertilizer comprised processed dry swine manure with the following composition: 33.60% organic matter, 1.05% nitrogen (N), 1.82% phosphorus pentoxide (P₂O₅), and 1.66% potassium oxide (K₂O), with a pH of 8.4 (on a dry weight basis). This material was sourced from Qujing Kangzhuang Fertilizer Industry Co., Ltd., Qujing, China. The details on the applied fertilizer quantities are listed in Table 1. Each experimental plot had an area of 30 m² (8.33 m × 3.6 m). The test crop was maize (*Zea mays* L. cv. Xuanhui 7), which is a high-yielding, disease-resistant cultivar widely cultivated in the target region. The experiment was conducted over a single growing season in 2022, with summer maize sown on 17 May and harvested on 9 October. Before sowing, all of the organic fertilizer, calcium superphosphate, and potassium sulfate, plus 20% of the urea, was broadcast and mixed with the topsoil layer (0–20 cm) by rotary tillage. The remaining urea was applied in two split applications during the maize jointing and tasseling growth stages. No artificial irrigation was used throughout the growth cycle, and the crops relied

solely on natural rainfall. All other management practices, including pest, disease, and weed control, were consistent across treatments.

Table 1. Fertilization amount of each treatment.

Treatment	Chemical Fertilizer (kg·ha ^{−1})			Organic Fertilizer (kg·ha ^{−1})	Total Conversion (kg·ha ^{−1})		
	Urea	Superphosphate	Potassium Sulphate		N	P ₂ O ₅	K ₂ O
NF	0	0	0	0	0	0	0
STF	743.55	562.50	180.00	0	345.00	90.00	90.00
OF15	631.95	1.80	16.35	4928.55	345.00	90.00	90.00
OF30	520.50	0	0	9857.09	345.00	179.40	163.63

Total conversion refers to the sum of nutrient equivalents (N, P₂O₅, K₂O) supplied from both organic and inorganic fertilizer sources.

2.3. Sample Collection and Index Determination

During maize maturity, three observation points per plot were selected. The plant height, stem diameter, and ear height of five consecutive plants were measured at each point using tape measures or vernier calipers [37]. At the maize harvest stage, the entire plot's yield was measured, and indoor seed testing was conducted post-harvest to record economic traits such as ear length, ear diameter, ear rows, row number, bald tip length, and 100-grain weight [38]. Prior to maize harvest, soil samples were collected from the undisturbed plow layer (−20 cm) in each plot. Following the “S” method, five soil samples were taken from the plow layer (−20 cm) using an auger corer positioned approximately 20 cm away from the plants. These samples were then combined to create a single homogeneous bulk soil sample per plot. Visible residues such as rocks, roots, and organic debris were removed by sieving through a 2 mm mesh, and the samples were stored at a temperature of 4 °C [39]. Subsequently, the soil was air-dried and sieved through a 0.25 mm sieve for the analysis of its physicochemical properties.

Soil pH was measured using a pH meter (PE28, Mettler Toledo, Zurich, Switzerland) at a soil-to-water ratio of 1:5 (*w/v*). The cation exchange capacity (CEC) was determined using the hexamine cobalt trichloride spectrophotometric method and a spectrophotometer (UV-1200, Shanghai, China) [40]. The soil organic matter (SOM) content was determined using the K₂Cr₂O₇ volumetric method [41]. Total nitrogen (TN) was measured using a Kjeldahl nitrogen analyzer (K9840, Dezhou, China), and total phosphorus (TP) was measured using the molybdenum blue colorimetric analysis via a spectrophotometer (UV-1200, Shanghai, China) [42]. Total potassium (TK) was determined via flame photometry (FP640, Shanghai, China) [43]. Hydrolyzable nitrogen (AN) was determined by the alkali diffusion method absorbed in boric acid [44]. Soil available phosphorus (AP) was determined after extraction with 0.5 M NaHCO₃ using the ammonium molybdate-ascorbic acid method and a spectrophotometer (UV-1200, Shanghai, China), and soil available potassium (AK) was measured using flame photometry (FP640, Shanghai, China) in ammonium acetate (NH₄OAc) extract [45].

2.4. Economic Analysis

This field experiment focuses on assessing the efficiency of various fertilizer products. Costs included organic fertilizer, urea, superphosphate, and potassium sulfate, but excluded expenses related to seeds, pesticides, and labor, as these inputs were assumed to be constant across treatments. The yield of each treatment was monetized using a unit price of 3.00 CNY·kg^{−1} at harvest. Economic returns were determined by following the methodology outlined by Liu et al. [46].

The economic benefit (E_b) was calculated as follows:

$$E_b = Y \times U_p \quad (1)$$

where Y is the maize yield ($\text{kg} \cdot \text{ha}^{-1}$) and U_p is the unit price ($\text{CNY} \cdot \text{kg}^{-1}$).

The net profit (N_p) was calculated as follows:

$$N_p = E_b - F_w \quad (2)$$

where F_w is the fertilizer input ($\text{CNY} \cdot \text{ha}^{-1}$).

The economic benefit growth (E_g) was calculated as follows:

$$E_g = \frac{E_{bi} - E_{bc}}{E_{bc}} \quad (3)$$

where E_{bi} is the economic benefit of the treatments ($\text{CNY} \cdot \text{ha}^{-1}$) and E_{bc} is the economic benefit of no fertilization ($\text{CNY} \cdot \text{ha}^{-1}$, NF).

The net profit growth (N_g) was calculated as follows:

$$N_g = \frac{N_{pi} - N_{pc}}{N_{pc}} \quad (4)$$

where N_{pi} is the net profit of the treatments ($\text{CNY} \cdot \text{ha}^{-1}$) and N_{pc} is the net profit of no fertilization ($\text{CNY} \cdot \text{ha}^{-1}$, NF).

2.5. Data Analysis

One-way ANOVA with LSD post hoc testing (SPSS 26.0, SPSS Inc., Chicago, IL, USA) identified significant differences ($p < 0.05$) in soil physicochemical properties, maize agronomic traits, and yield among fertilizer treatments, with data expressed as the mean $\pm$ SD. Relationships between soil properties and maize yield were analyzed using Pearson correlation and principal component analysis (PCA), visualized in Origin 2021 (OriginLab, Northampton, MA, USA).

3. Results

3.1. Physicochemical Properties of Soil

Figure 1 illustrates the impact of various fertilization treatments on soil physicochemical properties. In Figure 1a, it is evident that the STF treatments lead to soil acidification, resulting in a decrease in pH from 6.07 in the NF treatment to 5.44. Conversely, substituting a portion of nitrogen fertilizer with organic fertilizer increases soil pH, with the pH reaching 6.29 in the OF30 treatment, which is significantly higher than that in the STF treatment. The total phosphorus content in the OF30 treatment is notably higher than that in the NF and STF treatments. Soil nutrient availability is crucial for crop growth and is a key indicator of soil quality. Substituting nitrogen with organic fertilizer leads to a significant increase in the soil's available phosphorus content compared to the NF treatment. Soil organic matter, cation exchange capacity, total nitrogen, total potassium, hydrolyzable nitrogen, and available potassium show no significant changes when nitrogen is partially replaced with organic fertilizer. The above results show that substituting nitrogen fertilizer with organic fertilizer can mitigate the soil acidification induced by chemical fertilizers and optimize soil physicochemical properties.

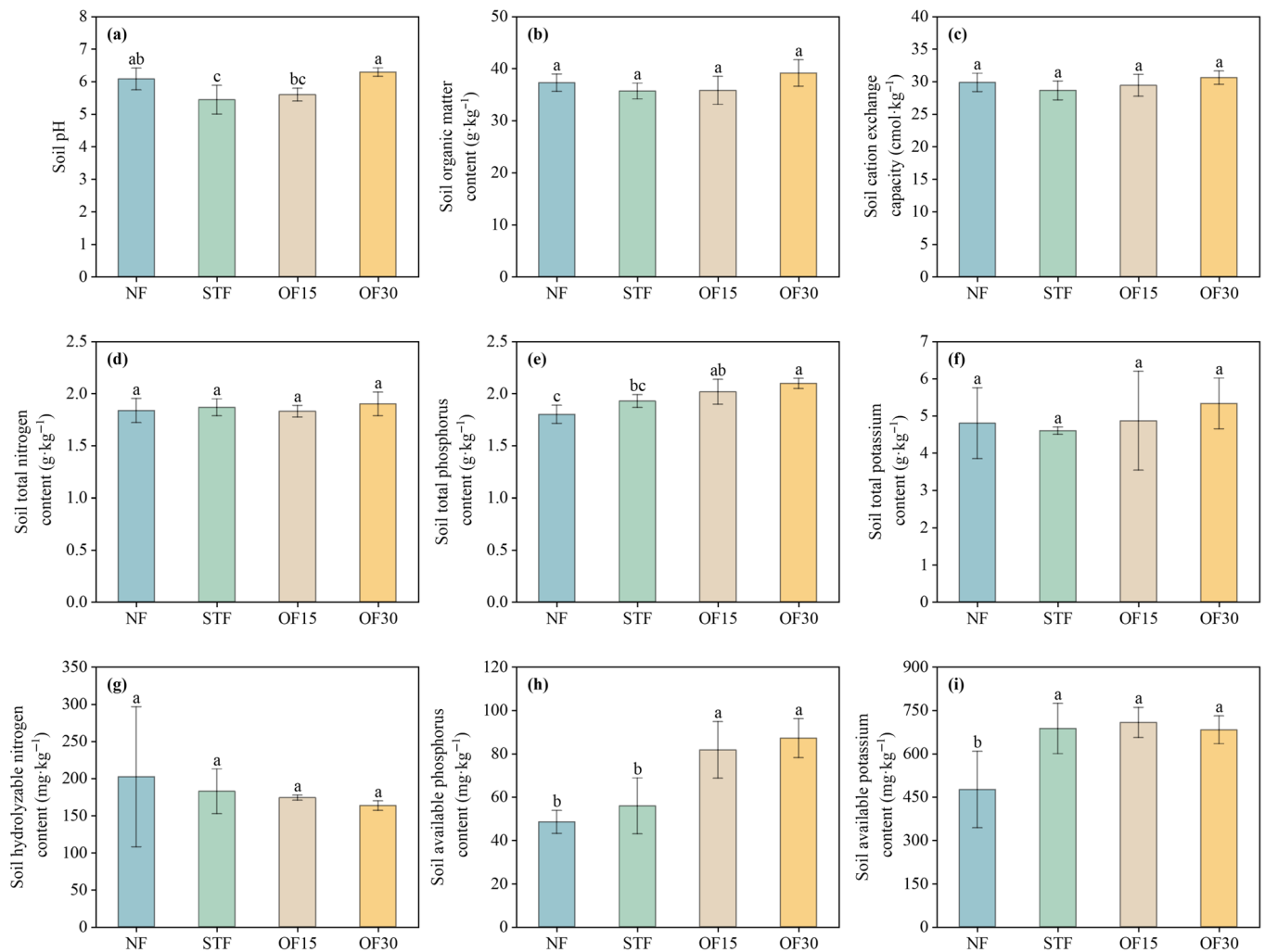


Figure 1. Soil physicochemical properties of maize under different treatments: no fertilization (NF), soil testing formula fertilization (STF), organic fertilizer replacing 15% of nitrogen fertilizer (OF15), and organic fertilizer replacing 30% of nitrogen fertilizer (OF30). (a) Soil pH; (b) soil organic matter content; (c) soil cation exchange capacity; (d) soil total nitrogen content; (e) soil total phosphorus content; (f) soil total potassium content; (g) soil hydrolyzable nitrogen content; (h) soil available phosphorus content; (i) soil available potassium content. Different lowercase letters indicate significant differences (LSD test, $p < 0.05$). Bars above columns indicate $\pm$ SD, $n = 3$.

3.2. Agronomic Traits of Maize

Chemical and organic fertilizers significantly enhanced maize growth (Figure 2). Specifically, the STF treatment increased plant height by 5.21% (from 282.33 cm to 297.03 cm) compared to NF. Treatments that substituted a portion of nitrogen fertilizer with organic fertilizer (OF) further enhanced plant height by 1.09% (OF15) and 1.93% (OF30) over STF. Moreover, stem diameter increased by 20.81% in STF (2.67 cm) versus NF (2.21 cm). The OF30 treatment outperformed STF, increasing stem diameter by an additional 6.24%. Similarly, STF increased ear height by 10.58% compared to NF, while OF treatments increased it by 3.64% (OF15) and 6.79% (OF30) compared to STF. Fertilizer applications also enhanced yield-related traits: OF treatments increased ear length by 6.56% (OF15) and 11.15% (OF30) and reduced bald tip length by 37.33% (OF15) and 44.00% (OF30) in comparison to STF. In addition, the OF30 treatment resulted in a significantly higher number of kernels per row compared to other treatments. Notably, there were no significant differences in plant height, stem diameter, ear length, ear diameter, kernel rows, or bald tip length between the OF15 and OF30 treatments. Overall, the maize agronomic traits obtained with OF15 and

OF30 nitrogen fertilizer replacements surpassed those of NF and STF treatments, with the OF30 treatment exhibiting the most favorable agronomic characteristics.

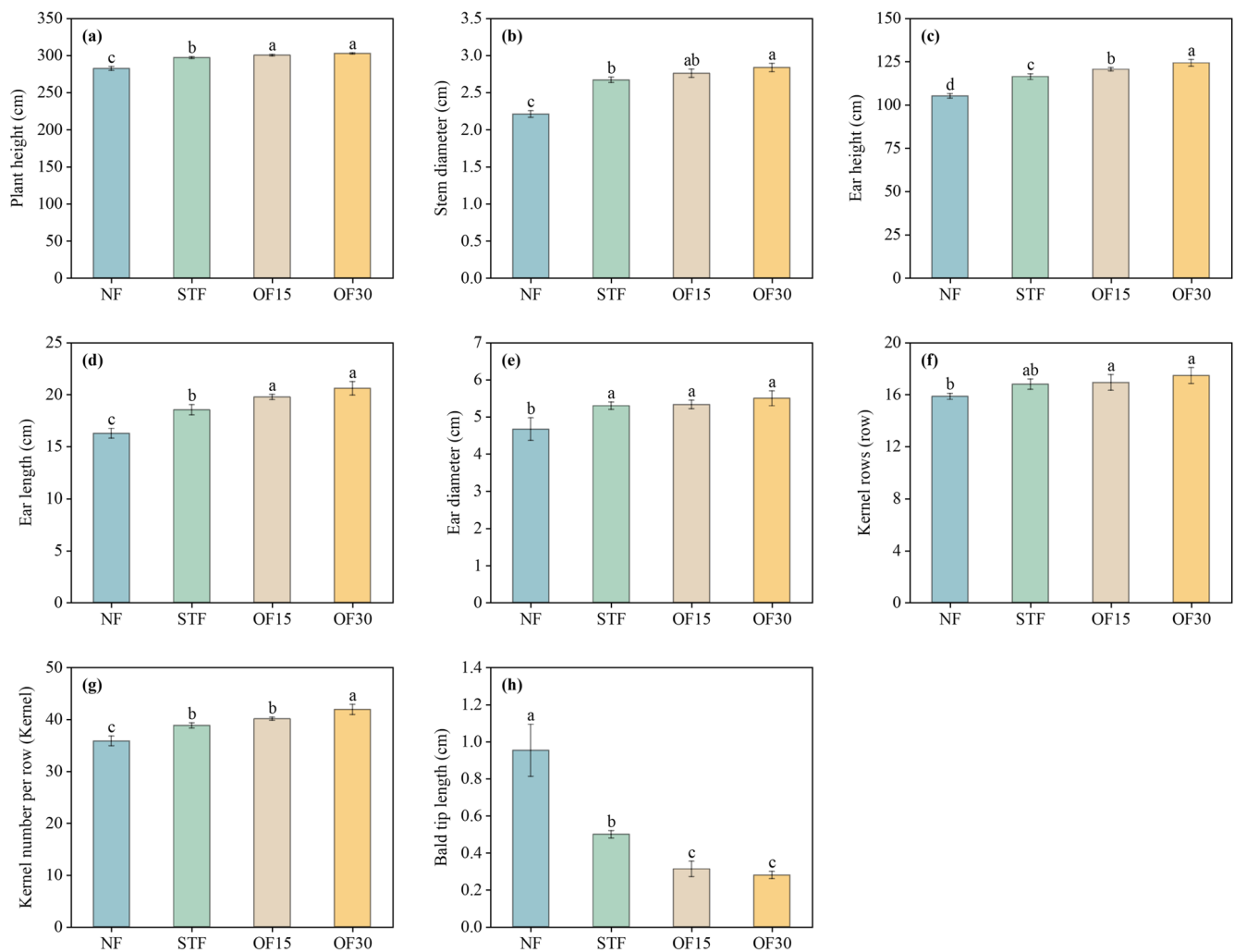


Figure 2. Agronomic traits of maize under different fertilizer treatments: no fertilization (NF), soil testing formula fertilization (STF), organic fertilizer replacing 15% of nitrogen fertilizer (OF15), and organic fertilizer replacing 30% of nitrogen fertilizer (OF30). (a) Maize plant height; (b) maize stem thickness; (c) maize ear position height; (d) maize spike length; (e) maize spike diameter; (f) maize kernel rows; (g) maize kernel number per row; (h) maize bald tip length. Different lowercase letters indicate significant differences (LSD test, $p < 0.05$). Bars above columns indicate $\pm$ SD, $n = 3$.

3.3. Maize Yield

Maize yield responded differentially to fertilizer treatments (Figure 3). In comparison to the NF treatment, all fertilizer treatments led to a significant increase in 100-grain weight. Specifically, the STF treatment exhibited a 5.23% increase in 100-grain weight compared to the NF treatment. Moreover, substituting a portion of nitrogen fertilizer with organic fertilizer (OF) increased 100-grain weight by 5.81% (OF15) and 8.84% (OF30) compared to STF, achieving final weights of 32.88 g (OF15) and 33.82 g (OF30), respectively. Regarding maize yield, both treatments with fertilizer and those substituting a portion of nitrogen fertilizer with organic fertilizer resulted in a significant increase in crop yield. The STF treatment increased maize yield by 22.53% compared to NF. OF treatments further improved yield by 8.92% (OF15) and 13.44% (OF30) compared to STF, but OF15 and OF30 did not differ significantly. Overall, partial substitution of nitrogen fertilizer with formulated organic fertilizer improved maize yield and 100-grain weight.

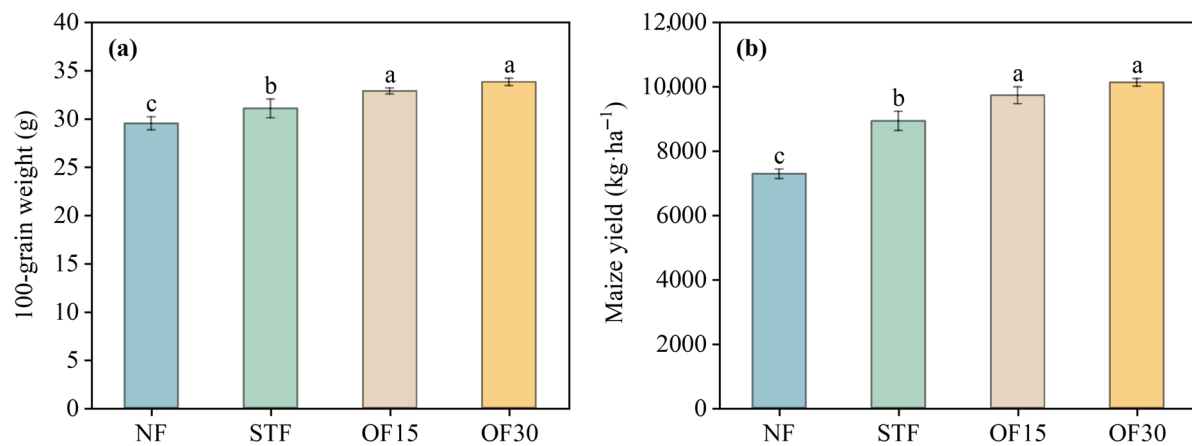


Figure 3. Yield of maize under different fertilizer treatments: no fertilization (NF), soil testing formula fertilization (STF), organic fertilizer replacing 15% of nitrogen fertilizer (OF15), and organic fertilizer replacing 30% of nitrogen fertilizer (OF30). (a) Maize 100-grain weight; (b) maize yield. Different lowercase letters indicate significant differences (LSD test, $p < 0.05$). Bars above columns indicate $\pm$ SD, $n = 3$.

3.4. Crop Economic Benefit

Table 2 demonstrates the significant impact of various fertilization strategies on the economic returns of maize cultivation. Substituting nitrogen fertilizer with organic fertilizer, particularly in the OF30 treatment, substantially enhances the total output value of maize production. The OF30 treatment yielded the highest total output value of 30,396.21 CNY·ha⁻¹, representing a 13.43% increase compared to the STF treatment, equivalent to a gain of 3599.95 CNY·ha⁻¹. Moreover, the net profit of the OF30 treatment notably surpassed that of the NF, STF, and OF15 treatments, reaching 25,981.73 CNY·ha⁻¹. Specifically, the net profit of the OF30 treatment outperformed that of the STF treatment by 2493.70 CNY·ha⁻¹, reflecting an 10.62% increase. In summary, adopting the OF30 treatment proves advantageous in maximizing profits while ensuring yield enhancement.

Table 2. Economic benefits of maize under different fertilizer treatments.

Treatment	Yield (kg·ha ⁻¹)	Fertilizer Input (CNY·ha ⁻¹)	Economic Benefit (CNY·ha ⁻¹)	Net Profit (CNY·ha ⁻¹)	Economic Benefit Growth (%)	Net Profit Growth (%)
NF	7289.89 ± 145.72 ^c	0	21,869.67 ± 437.14 ^c	21,869.67 ± 437.14 ^c	0	0
STF	8932.09 ± 298.41 ^b	3308.23	26,796.26 ± 895.21 ^b	23,488.03 ± 895.21 ^b	22.52 ± 4.09	7.4 ± 4.09
OF15	9728.74 ± 261.66 ^a	3315.28	29,186.23 ± 784.99 ^a	25,870.94 ± 784.99 ^a	33.45 ± 3.59	18.29 ± 3.59
OF30	10,132.07 ± 122.22 ^a	4414.48	30,396.21 ± 366.65 ^a	25,981.73 ± 366.65 ^a	38.99 ± 1.68	18.8 ± 1.68

Treatment abbreviations: no fertilization (NF), soil testing formula fertilization (STF), organic fertilizer replacing 15% of nitrogen fertilizer (OF15), and organic fertilizer replacing 30% of nitrogen fertilizer (OF30). Different lowercase letters indicate significant differences (LSD test, $p < 0.05$). Values are expressed as mean $\pm$ SD, $n = 3$.

3.5. Correlation Analysis Between Yield and Soil Physicochemical Properties

PCA analysis of the soil's physicochemical properties and yield revealed that PC1 (34.6%) and PC2 (23.1%) captured 57.7% of the total variance, indicating additional factors (Figure 4a). PC1 exhibited a negative correlation with CEC and a positive correlation with other parameters, while PC2 was mainly associated with pH and AN. The OF15 and OF30 treatments were situated on the positive axis of PC1, which was positively linked to TN, TP, AP, and yield. Significantly differing from the NF treatment along the PC1 axis, the OF15 and OF30 treatments demonstrated enhanced soil properties and increased yield, suggesting the beneficial impact of substituting organic fertilizer for chemical fertilizer.

Pearson correlation analysis further confirmed positive relationships between maize yield and soil properties. Specifically, yield correlated strongly with AP ($r = 0.66$, $p < 0.01$) and weakly with TP ($r = 0.63$, $p < 0.05$). Notably, significant interrelationships emerged among other soil parameters: AK demonstrated a strong positive correlation with AP ($r = 0.72$, $p < 0.01$), a weak positive correlation with TP ($r = 0.61$, $p < 0.05$), and a weak negative correlation with pH ($r = -0.54$, $p < 0.05$), while SOM exhibited a strong positive correlation with TN ($r = 0.77$, $p < 0.01$) and a weak positive correlation with TK ($r = 0.53$, $p < 0.05$). These patterns elucidate the mechanisms underlying soil properties' influence on maize productivity (Figure 4b).

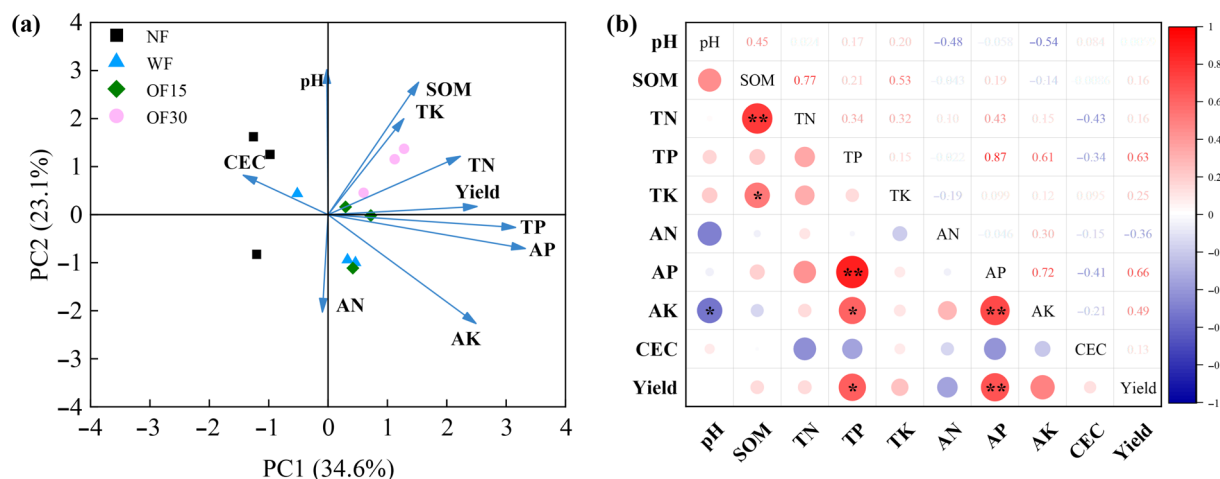


Figure 4. Correlation analysis between yield and soil physicochemical properties. (a) Principal component analysis of maize yield and soil physicochemical properties; (b) Pearson correlation analysis between maize yield and soil physicochemical properties. Red indicates positive correlations, while blue indicates negative correlations. Treatment abbreviations: no fertilization (NF), soil testing formula fertilization (STF), organic fertilizer replacing 15% of nitrogen fertilizer (OF15), and organic fertilizer replacing 30% of nitrogen fertilizer (OF30). Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.01$). Abbreviations: SOM (soil organic matter), TN (total nitrogen), TP (total phosphorus), TK (total potassium), AN (hydrolyzable nitrogen), AP (available phosphorus), AK (available potassium), CEC (cation exchange capacity), Yield (maize yield).

4. Discussion

4.1. Effects of Different Fertilization Treatments on Soil Physicochemical Properties

The study demonstrated that substituting organic fertilizer for nitrogen fertilizer enhanced red soil properties in Yunnan. The application of chemical fertilizers (STF) resulted in a significant decrease in soil pH, with nitrogen input identified as a key factor in soil acidification [47]. Our observed pH decline under nitrogen fertilizer application aligns with the established mechanisms reported in the literature [48,49]. Previous research indicates that urea-based nitrogen fertilizers can trigger ammoniation and nitrification processes, potentially leading to leaching losses of alkaline cations alongside nitrate anions [50,51]. Conversely, organic manure's alkalinity (pH 8.4) and reduced nitrification from lower urea use jointly raised soil pH [52]. Moreover, it may also be attributed to the input of substantial alkaline cations (Ca^{2+} , Mg^{2+}) from organic fertilizer [53], the decarboxylation of organic anions releasing OH^- during organic carbon mineralization, and the protonation of organic molecules consuming H^+ [54,55]. Additionally, previous studies have reported that organic fertilizer application was observed to effectively ameliorate soil acidification by promoting nitrogen mineralization, enhancing ammonium immobilization, facilitating autotrophic nitrification, and increasing nitrate consumption [56–58].

The results indicate no significant differences in SOC, CEC, N, and K content among the treatments. This may be explained by the soil testing formula fertilization approach, which ensured precise nutrient inputs that likely approximated crop uptake [59], potentially limiting soil residue accumulation, and the experimental soil's inherently high fertility, which may have diminished the additional effect of short-term fertilization. Similarly, CEC stability suggests that organic inputs need longer durations to impact cation retention [60,61]. Conversely, substituting nitrogen fertilizer with organic fertilizer could enhance TP and AP content. Application of organic and inorganic fertilizers was found to enhance the accumulation of total phosphorus and total potassium in soil. Specifically, the TP content in the OF30 treatment was significantly higher compared to the STF treatment. OF30 increased AP by 56.02% versus STF, likely via organic acid-driven P solubilization [62,63]. Furthermore, certain oxygen-soluble organic groups can also compete with phosphate anions for adsorption sites, facilitating phosphorus release [64]. Additionally, dissolved organic matter can form complexes with iron and aluminum oxides, encapsulating soil mineral phosphorus adsorption sites and reducing phosphorus adsorption likelihood [62,65]. Zhang et al. [66] showed that high substitution rates of manure that is used as a phosphorus source significantly decreased the solubility of inorganic phosphorus while enhancing the mineralization capacity of organic phosphorus.

4.2. Effects of Different Fertilization Treatments on Maize Agronomic Characteristics

Agronomic traits are key indicators of crop growth and development, while crop yield serves as a crucial measure for assessing changes in soil fertility [67,68]. Utilizing scientific fertilization models can enhance crop agronomic traits and boost crop productivity [69]. By partially substituting chemical fertilizer with organic fertilizer, a balance can be struck between the longevity of organic fertilizer and the immediacy of chemical fertilizer, ensuring a rapid supply of essential nutrients during the initial growth stages and serving as a consistent nutrient source throughout subsequent crop development [70]. Additionally, organic fertilizers may promote soil aggregate formation, potentially improving soil structure to enhance water infiltration and retention, aeration, and root development, which can ultimately benefit maize growth [71,72]. Studies indicate that the combined application of organic and inorganic fertilizers can enhance the nutrient uptake efficiency of maize, leading to increased nutrient accumulation [73–75]. The study by Mahmood et al. [76] found that the combined application of organic and inorganic fertilizers significantly enhanced maize growth, markedly increasing leaf area and biomass. Similarly, studies by He et al. [77] demonstrated that partial substitution of chemical fertilizers with organic manure during application can increase the plant height and stem diameter of maize at various growth stages, effectively improve ear traits (with significant increases in ear length and the number of rows per ear), and enhance yield-related traits. Our investigation revealed that maize treated with varying ratios of organic and chemical fertilizers exhibited superior agronomic traits—such as plant height, stem diameter, ear length, crown size, ear height, kernels per row, and rows per ear—compared to those treated solely with soil testing formula fertilizer. These findings underscore the potential of well-suited organic and chemical fertilizers to stimulate maize growth and elevate maize yield in the typical red soil region of Yunnan Province.

4.3. Effects of Different Fertilization Treatments on Maize Yield and Economic Benefit

The application of organic fertilizer as a partial replacement for chemical fertilizer has been shown to enhance soil physicochemical properties, increase TP and AP levels, and boost maize yield. The higher 100-grain weight observed in OF30 indicates improved seed filling, potentially enhancing market value. Critically, enhanced agronomic traits

directly contributed to the increased maize grain weight. However, PC1 and PC2 explained 57.7% of the variance, suggesting that other factors, such as improvements in soil physical properties (e.g., bulk density, aggregates) or rhizosphere microbial collaboration, may also influence yield [71,78], warranting further investigation.

This study observed an increase in TP and AP following the use of organic substitute fertilizer. The alteration of soil phosphorus content was a primary driver of yield enhancement under organic substitution. Notably, maize yield exhibited higher correlation with AP ($r = 0.66$, $p < 0.01$), suggesting improved P uptake (Figure 4b). Previous studies suggest that phosphorus uptake in maize grains primarily occurs through root absorption during the later stages of growth, with minimal contribution from phosphorus transfer in the early vegetative phase [79]. The accumulation of phosphorus uptake during the middle and late stages of maize growth constitutes approximately 50% of the entire growth period [80], underscoring the essential role of phosphorus in maize yield formation. The present study demonstrated that, compared to other treatments, a significantly higher maize yield occurred when organic fertilizer partially replaced nitrogen fertilizer, with yield increasing proportionally to the replacement ratio. This outcome may be due to the elevated inputs of P_2O_5 and K_2O under higher nitrogen substitution rates in OF30 compared to those of STF and OF15. The gradual release of nutrients from organic fertilizer can fulfill the phosphorus requirements during the middle and late stages of maize growth [70], thereby promoting yield enhancement. Organic fertilizer application can elevate acid and alkaline phosphatase levels in soil, alter the form of phosphorus in red soil, boost the diversity of the microbial community carrying the alkaline phosphatase gene, and facilitate crop phosphorus accumulation [81]. Zhang et al. [82] demonstrated that organic fertilizer stimulated the activity and abundance of microorganisms involved in phosphorus mobilization processes, thereby improving soil phosphorus cycling and availability and promoting crop yield increase.

However, despite the higher P_2O_5 inputs of OF30, its yield did not differ significantly from OF15. This yield plateau suggests that phosphorus sufficiency was achieved at the 15% substitution level [83], with the additional phosphorus in OF30 providing no further yield benefit. The OF30 treatment is robustly recommended for maximizing profitability and sustainability. It achieved the highest net profit ($25,981.73 \text{ CNY} \cdot \text{ha}^{-1}$), outperforming STF by 10.62% despite higher manure costs, while delivering a 38.99% economic benefit increase over NF. This cost effectiveness aligns with Sustainable Development Goal 2 (SDG 2) by enhancing productivity while increasing economic benefits through organic soil amendments, a critical pathway toward sustainable intensification [84].

5. Conclusions

In conclusion, the application of organic fertilizer as a partial substitute for nitrogen fertilizer in the typical red soil farmland in Yunnan Province has been found to elevate soil pH, as well as increase TP and AP contents. Maize plants treated with organic fertilizer partially replacing nitrogen fertilizer exhibited superior agronomic traits, including plant height, stem diameter, bald tip length, and ear height, compared to those subjected to direct chemical fertilizer application and formula fertilization based on soil testing. The OF30 treatment exhibited the highest maize yield at $10,132.07 \text{ kg} \cdot \text{ha}^{-1}$ and generated the highest net profit of $25,981.73 \text{ CNY} \cdot \text{ha}^{-1}$. Principal component analysis revealed a positive correlation between maize yield and soil TP as well as AP. This suggests that soil total phosphorus and available phosphorus are the primary limiting factors for maize yield following the substitution of nitrogen fertilizer with organic fertilizer. To advance the scientific understanding and practical application of this approach, future studies should investigate microbially mediated phosphorus transformation mechanisms under continuous organic substitution, optimize substitution ratios by integrating soil carbon–

phosphorus stoichiometry with crop nutrient use efficiency, and assess carry-over effects on subsequent crops through field trials.

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