Industrial Crops & Products 242 (2026) 122923

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Response characteristics of maize yield and partial factor productivity of nitrogen to biochar addition in China based on meta-analysis

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ARTICLE INFO

Keywords:
Biochar addition
Maize
Yield
Partial factor productivity of nitrogen
Meta-analysis
Machine learning

ABSTRACT

Biochar addition is an effective measure to enhance agricultural productivity and improve soil fertility. However, the response of agricultural productivity to biochar addition varies greatly depending on the production background. In this study, meta-analysis and machine learning methods were used to systematically analyze the effects of biochar addition on maize yield and partial factor productivity of nitrogen (PFPN) in China. The results showed that: 1) Maize yield and PFPN with biochar addition could be significantly increased by 10.49 %-15.02 % and 13.32 %-18.26 %, respectively. 2) In terms of region, year and field management, biochar addition demonstrated more significant yield-enhancing effects in South China under the following conditions: average annual precipitation $\geq$ 800 mm, average annual temperature $\geq$ 16℃, biochar application duration of 2 years, biochar application amount of 25–35 kg·ha^{-1} and planting density $\geq$ 90,000 plants·ha^{-1}. The PFPN-improving effects were most pronounced in Northwest China under the following conditions: average annual precipitation < 200 mm, average annual temperature 8–12℃, biochar application duration of 1 year, biochar application amount of $\geq$ 35 kg·ha^{-1} and planting density $\geq$ 90,000 plants·ha^{-1}. 3) In the soil environment, the growth rates of yield and PFPN varied with different environmental factors (e.g., soil type, texture and physical properties), and the growth rates remained within the ranges of 4.07 %-56.55 % and 5.17 %-45.64 %, respectively. 4) Analysis using Random Forest, Gradient Boosting Machine, and multi-factor optimization models revealed that maize yield was primarily regulated by the synergistic effects of annual average temperature, experimental year, biochar application amount, and soil total nitrogen content. Meanwhile, PFPN exhibited more sensitive responses to experimental duration, biochar application amount, soil texture, soil pH, and soil total nitrogen content. In conclusion, this study systematically clarified the mechanism by which biochar enhances maize productivity, providing scientific basis and technical support for high-yield and efficient maize cultivation in China and other similar ecological regions.

1. Introduction

In recent years, multiple crises such as population growth, climate change and agricultural activities have led to a series of increasingly severe ecological and environmental problems (Cheng et al., 2024), such as drastic reduction of cultivated land, extreme weather, greenhouse effect and soil degradation (Azim et al., 2024, Xue et al., 2019, Singh et al., 2021), posing major challenges to the realization of global food security and sustainable agricultural development strategies (Wu et al., 2025). Therefore, how to improve farmland quality and enhance grain production capacity to meet the demands of a growing population without increasing resource investment has become a central topic of global agricultural research. Crop growth and development are co-determined by multiple factors including genetic traits, biological environments and field management practices. Optimizing the coordination and management of these factors constitutes a critical step for enhancing crop productivity. Among various management factors, biochar, as a carbon-rich solid and stable organic material formed by pyrolysis of straw or organic waste under high-temperature oxygen-limited or anoxic conditions (Ali et al., 2021), has the characteristics of large specific surface area, well-developed pore structure and abundant surface functional groups (Rasul et al., 2022), and is a kind of green and safe soil improvement resource and agricultural input. It provides a new approach for addressing global food security problems and environmental changes (Waheed et al., 2025). Biochar addition, as a comprehensive and multi-functional soil management strategy, demonstrates

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https://doi.org/10.1016/j.indcrop.2026.122923
Received 25 October 2025; Received in revised form 15 January 2026; Accepted 13 February 2026

high application value and environmental benefits (Yang et al., 2023). It plays an important role in improving farmland quality, enhancing crop productivity, and promoting environmental protection (Abhishek et al., 2022, Sheer et al., 2024).

Some studies have demonstrated that biochar addition not only provides essential mineral elements for crop growth but also, through its porous structure, absorbs water and available nutrients in soil, and enhances soil fertility and water retention capacity. These improvements collectively promote nutrient cycling and absorption in crop roots, ultimately increasing crop yield potential and resource utilization efficiency (Kapoor et al., 2022). Notably, compared with no biochar addition, biochar can synergistically regulate nitrogen cycle process through various physical, chemical and microbial mechanisms, thereby improving soil nitrogen availability and enhancing the conversion ability of crop plants to fertilizer nitrogen (Prezafontes et al., 2013). These effects have been demonstrated to promote crop growth and significantly increase yields in tomato, rice, and wheat systems (Haider et al., 2020, Abdelghany et al., 2023, Zhang et al., 2024, Abbruzzini et al., 2019). However, some negative effects of biochar addition on soil environment and crop productivity have also been reported. Biochar typically exhibits alkaline properties. Under neutral or slightly alkaline soil conditions, excessive addition can lead to an excessively high soil pH value. An increase in soil pH will reduce the availability of micronutrients such as iron, manganese and zinc, hindering the absorption of sufficient essential elements by crop roots (Cao et al., 2018), and affecting soil fertility and crop yield. Studies have pointed out that while excessive biochar application can partially alleviate soil water deficit, it demonstrates no significant enhancing effect on crop yield and nitrogen uptake (Tammeorg et al., 2014). Further studies reveal that when biochar application exceeds the critical threshold of 0.8 $t\cdot ha^{-1}$ in facility lettuce cultivation, it not only disrupts soil nutrient balance, but also significantly reduces lettuce yield in the second season (by 12.97 %-19.87 %) (Lee et al., 2024). It can be seen from this that there are still significant differences or conflicting results in the current research on crop productivity response to biochar addition, which further highlights the necessity of studying the effects of biochar addition. Therefore, more information on crop responses to biochar addition is required to evaluate the feasibility of this management practice and maximize its potential in agricultural production.Maize (*Zea mays* L.) is a globally significant “grain-feed-economy” multi-purpose crop, ranking third in cultivation area after rice and wheat (Li et al., 2018), and contributing approximately 35 % of the total global grain production (FAO, 2018). As the world’s second largest maize producer, in 2025, China’s maize planting area reached 44.93 million ha, accounting for 37.63 % of the total grain planting area; the annual output reached 301.24 million tons, accounting for 45.63 % of the total grain production (https://www.stats.gov.cn/). However, the intensive production of maize in China remains constrained by the traditional planting model of “high-input-high-yield” (Wang et al., 2023), and generally faces many problems including excessive fertilizer dependency, low resource use efficiency, prominent bottleneck of yield-increasing and environmental deterioration (Tian et al., 2024). These problems have led to an imbalance between supply and demand of maize in the domestic market, with annual import dependence of maize up to 28 million tons (Zhao and He, 2024). Therefore, under the background of efficient agricultural production, how to formulate a new maize planting strategy to resolve the ecological dilemma of maize production is of great strategic significance for ensuring the global food abundance and stable production, and sustainable supply of agricultural products. Undoubtedly, biochar addition is gradually being introduced into maize production practices.

At present, many scholars have conducted a great deal of research around the effects of biochar addition on maize productivity. Field studies have shown that biochar, as a sustainable soil conditioner, has a significant long-term effect (Cruz et al., 2024). Under the condition of reducing nitrogen fertilizer application by 20 %-40 %, adding biochar (16 $t\cdot ha^{-1}$) can promote the growth (plant height, stem diameter, leaf area index and dry matter accumulation) and nitrogen utilization of maize by increasing soil organic carbon and total nitrogen content. Moreover, the yield-increasing effect shows obvious temporal dynamic characteristics, that is, maize yield reaches the peak in the second year and continues into the third growth season (Zhang et al., 2025). It is worth noting that biochar application (9 $t\cdot ha^{-1}$) combined with plastic film mulching measures can further strengthen the soil improvement effect. On the one hand, it significantly enhances the soil nutrient retention capacity; on the other hand, it effectively improves the maize yield (by 13.9 %-45.1 %) and nitrogen use efficiency (by 12.1 %-74.8 %), and reduce the ineffective nitrogen loss in farmland (including gaseous nitrogen loss and nitrogen leaching) (Liu et al., 2022). However, most of these studies belong to independent sits studies, and the response relationship of maize production effects to biochar addition at different regional scales remains unclear. For instance, are there any specific environmental conditions for the positive effects of biochar addition on maize production and the strength of these positive effects? What are the main factors affecting maize production and the extent of their influence? All need to be further discussion.

Meta-analysis is a systematic statistical analysis method based on the principles of evidence-based science, which realizes the integration and quantitative analysis of research results through strict literature screening, data extraction, and statistical analysis on multiple independent studies under the same research topic (Hedges et al., 1999). Its core lies in that it can objectively and quantitatively evaluate the sources of variation among studies through standardized effect size calculation and heterogeneity test, reveal potential factors affecting the target variables at the regional or global scale, clarify its mechanisms of action and quantify the effect intensity (Wang et al., 2019, Du et al., 2018). In recent years, meta-analysis has developed into an indispensable analytical tool for ecological process assessment and agricultural system research with its objectivity, repeatability and large-scale multi-source integration ability. Machine learning is a branch of artificial intelligence and performs outstanding in agricultural data analysis. Its powerful algorithmic system can not only effectively deal with complex nonlinear relationships and multi-source high-dimensional data in agricultural systems, but also accurately identify the key driving factors affecting crop growth through feature importance selection, and quantify the influence degree and direction of each factor (Tang et al., 2024). Thus, the integration of meta-analysis with machine learning enables a systematic quantification of climate-soil-management interactions, overcomes the limitations of traditional statistical methods in modeling nonlinear responses, and provides mechanistic insights into the effects of agricultural management. In the field of agricultural science, existing studies have combined meta-analysis and machine learning, aiming to evaluate the regional adaptability of different agronomic measures, and quantify key environmental factors affecting yield and their relative contributions across different planting systems, including cotton, wheat and rice (Liang et al., 2025, Wang et al., 2025, Yao et al., 2025). However, the application of multiple machine learning methods to explore the relative contributions and importance ranking of various environmental factors, management practices, and their interactions on maize yield and partial factor productivity of nitrogen (PFPN) have not been fully considered.

In view of this, based on published data from China, this study employs meta-analysis and machine learning with the following objectives: (1) to systematically evaluate the overall and regional effects of biochar application on maize yield and nitrogen partial factor productivity (PFPN); (2) to examine how experimental regions, field management practices, and soil environmental conditions modulate these effects; (3) to determine optimal biochar application thresholds under different conditions and identify management strategies that can synergistically enhance both crop yield and PFPN; (4) to integrate Random Forest (RF), Gradient Boosting Machine (GBM), and multivariate optimization models to identify the key driving factors for improvements in yield and PFPN, providing theoretical support and practical guidance for the targeted and efficient application of biochar in China's maize production systems.

2. Materials and methods

2.1. Data sources

This study searched the China National Knowledge Infrastructure (CNKI, http://www.cnki.net/), the Web of Science (https://www.webofscience.com/) and Google Scholar (https://scholar.dosf.top/) for peer-reviewed papers the effects of biochar addition on maize yield and PFPN in China with a cut-off date of 15 December 2024. The search terms included biochar, maize/corn, yield, and partial factor productivity of nitrogen/PFPN. Since the design and management of field trials vary considerably, we developed a unified search criteria to screen the literature and minimize analytical bias. The screening criteria were as follows: (1) studies must have been conducted in field conditions within China, with clearly reported locations and experimental years; (2) the trial treatments must include both added and unadded biochar; (3) papers must provide either direct reporting or calculable data (means ± standard deviation) for maize yield and PFPN under the relevant treatments; (4) studies involving additional fertilizer treatments or lacking appropriate control groups were excluded; (5) literature with high repetition rate of experimental content was excluded. After screening by the above criteria, a total of 68 papers were obtained, containing 409 sets of yield and 321 sets of PFPN data. The yield and PFPN data were either derived from tables and text or from figures (extracted using Get Data Graph Digitizer software).

2.2. Data classification

To more precisely analyze the effects of biochar addition on maize yield and PFPN, the experimental duration in this study was categorized into five temporal scales [1 year (1 a), 2 years (2 a), 3 years (3 a), 4 years (4 a) and ≥ 5 years (5 a)] to assess time-dependent responses based on data volume and distribution characteristics. The study area was stratified into seven geographic regions (Northeast China, North China, East China, Central China, South China, Northwest China, and Southwest China) to improve spatiotemporal representativeness (Hu et al., 2024). In addition, by synthesizing the data acquisition and prior research experience, we focused on the six most prevalent biochar feedstock types by sample size: firewood, rice husk, rice straw, cotton straw, wheat straw, and maize straw. Regarding maize varieties, the nine maize varieties with the largest sample sizes were selected: Chengyu 788, Dafeng 30, Demeiya No. 1, Liangyu 777, Nandan 19, Suyu 29, Ximeng No. 6, Xianyu 335, and Zhengdan 958. Meanwhile, soil types were divided into eleven categories according to the *China Soil Classification* and *Codes 2009* (GB/T 17296–2009, 2009): meadow soil (MeS), moist soil (MS), black soil (BS), red soil (RS), loess soil (LS), and gray soil dust (DS), Forest soil (FS), sandy soil (SS), moist soil (MoS), saline soil (SaS), and palm soil (PS); soil texture was classified into five categories: clay (C), light clay loam (LCL), silty loam (SL), loam (L), and sandy loam soil (SLS). Furthermore, this study incorporated other variables that may influence treatment effects, including climatic conditions, biochar properties, planting management practices, and soil environmental factors, with detailed classifications provided in Table 1.

2.3. Data analysis

2.3.1. Calculation of standard deviation

Standard deviation was used as an important meta-analysis parameter to calculate the weights of each study. During the process of data collation, if the standard deviations of yield and PFPN were listed in the literature, it could be used directly; if the standard deviation was lacking in the literature, the method of Gattinger et al. (2012) was referred to instead.

2.3.2. Calculation of effect size

The effect size is an indicator for measuring the magnitude of the treatment effect. In our study, the natural logarithmic of the response ratio (R) was calculate as the effect size (Du et al., 2018):

$$lnR = ln(X_a/X_c) \tag{1}$$

Where X_a and X_c represent the maize yield (kg·ha^{-1}) or PFPN (kg·kg^{-1}) with and without biochar addition.

The within variance (v_i) was calculated:

$$v_i = \frac{S_a^2}{n_a X_a^2} + \frac{S_c^2}{n_c X_c^2} \tag{2}$$

Where v_i represents the within variance of the case, S_a and S_c represent the standard deviation of maize yield or PFPN with and without biochar, respectively, with n_a and n_c representing the corresponding numbers of replications.

The cumulative effect size was calculated using a weighted calculation method, that is, each individual sample was given a specific weight w (i.e., the inverse of the variance v_i) to compensate for the precision between different samples. The weighted effect size (lnR^+) and its

Table 1
Subgroup classification of influencing factors.

Influence factors	Index	Subgroup				
		1	2	3	4	5
Climate factors	Average annual precipitation (AAP)/mm	< 200	200–400	400–800	≥ 800	
	Average annual temperature (AAT)/℃	< 4	4–8	8–12	12–16	≥ 16
Biochar factors	Pyrolysis temperature (PT)/℃	< 400	400–475	≥ 475	—	—
	Biochar pH	< 9	9–10	≥ 10	—	—
	Biochar C/N	< 60	60–70	≥ 70	—	—
	Biochar application duration/a	1a	2a	3a	> 3 a	
	Biochar application amount/t·ha^{-1}	< 5	5–15	15–25	25–35	≥ 35
Planting factors	Planting density (PD)/× 10^{4} plants·ha^{-1}	< 5	5–7	7–9	≥ 9	—
	Irrigation condition (IC)	Rainfed	Irrigation	—	—	—
	Soil bulk density (BD)/g·cm^{-3}	< 1.3	1.3–1.4	≥ 1.4	—	—
Soil environmental	Soil pH	< 6	6–8	≥ 8	—	—
	Soil organic matter (SOM)/g·kg^{-1}	< 10	10–20	≥ 20	—	—
	Soil alkaline nitrogen (Alk N)/mg·kg^{-1}	< 40	40–80	80–120	≥ 120	—
	Soil organic carbon (SOC)/g·kg^{-1}	< 10	10–20	≥ 20	—	—
	Soil total nitrogen (TN)/g·kg^{-1}	< 0.8	0.8–1.1	≥ 1.1	—	—
	Soil available nitrogen (AN)/mg·kg^{-1}	< 50	50–60	≥ 60	—	—
	Soil available phosphorus (AP)/mg·kg^{-1}	< 10	10–40	≥ 40	—	—
	Soil available potassium (AK)/mg·kg^{-1}	< 120	120–160	≥ 160	—	—

confidence intervals (*CI*) can be obtained by *lnR* calculation.

The weight of the *i*th study (w_i) was calculated:

$$w_i = 1/(v_i + \tau^2) \tag{3}$$

Where w_i represents the weight of the *i*th study and τ^2 represents the variance between cases.

Calculation of cumulative effect size (Qi et al., 2019):

$$lnR^+ = \sum_{i=1}^{k} w_i y_i \Big/ \sum_{i=1}^{k} w_i \tag{4}$$

$$S(lnR^+) = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i}} \tag{5}$$

$$95\%CI = lnR^+ \pm 1.96S(lnR^+) \tag{6}$$

Where k represents the sample number in the meta-analysis, lnR^+ represents the cumulative effect size, $S(lnR^+)$ represents the overall standard error, and 95 %*CI* represents 95 % confidence interval.

$$Z_a = [\exp(lnR) - 1] \times 100 \tag{7}$$

When the 95 %*CI* of Z_a are greater than zero, it indicates that biochar has a significant positive effect on increasing maize yield or improving PFPN. Conversely, if all of them are less than zero, it indicates that biochar has a significant negative effect on increasing maize yield or improving PFPN. If they contain zero, it indicates that biochar does not have a significant effect on increasing maize yield or improving PFPN.

2.3.3. *Heterogeneity test*

To analyze whether there were statistically significant differences exist among all studies in the same meta-analysis, heterogeneity analysis was tested using the *Q* statistic in our study. The calculation formula of the *Q* statistic was as follows (Card, 2011):

$$Q = \sum_{i=1}^{k} w_i (lnR_i)^2 - \frac{(\sum_{i=1}^{k} w_i lnR_i)^2}{\sum_{i=1}^{k} w_i} \tag{8}$$

When the *P*-value for the *Q* statistic (P_Q) was less than 0.05, the random-effects model was selected. Otherwise, the fixed-effects model was applied.

2.3.4. *Publication bias test*

In this study, Rosenthal's Fail-safe N was used for publication bias test. If $N > 5\,n + 10$ (n represents the sample size), the study was considered free from publication bias with high result reliability (Li et al., 2020).

2.3.5. *Analysis of influencing factors*

According to the data classification in Section 2.2, all indicators were stratified into different subgroups for separate meta-analyses to identify primary sources of heterogeneity across studies.

2.4. *Data processing*

The Microsoft Excel 2016 software was utilized to create the database, R (v. 4.2.2) programming software was adopted to analyze the data, and Origin 2021Pro software was used for plotting.

3. Results and analysis

3.1. *Data distribution and overview*

Due to climatic conditions and management practices, maize yield and PFPN with and without biochar addition showed large variability and favorable normal distribution characteristics (Fig. 1). In addition, the median range of maize yield with and without biochar addition was 5.56–12.20 t·ha^{-1} and 5.0–11.02 t·ha^{-1} for the 7 regions, and 9.76–12.95 t·ha^{-1} and 8.0–11.4 t·ha^{-1} for the 13 experimental years, respectively; the median range of PFPN was 12.0–74.14 kg·kg^{-1} and 11.11–67.84 kg·kg^{-1} for the 7 regions, and 13.64–67.33 kg·kg^{-1} and 11.11–55.84 kg·kg^{-1} for the 13 experimental years, respectively (Fig. 2).

3.2. *Comprehensive effect size and bias test*

Comprehensive effect size was calculated separately for maize yield and PFPN with biochar addition (Table 2). The results showed that the heterogeneity test of both maize yield and PFPN with biochar addition reached extremely significant levels ($P_Q < 0.001$); consequently, the random-effects model was adopted. Overall, compared to no biochar, maize yield and PFPN were increased by 12.73 % (95 % CI = 10.49 %-15.02 %) and 15.76 % (95 % CI = 13.32 %-18.26 %) with biochar addition, respectively. In conclusion, biochar application can significantly increase maize yield and PFPN. In addition, after the publication bias test, the Rosenthal's Fail-safe N for maize yield and PFPN were 5456,215 and 762,945, respectively, which were much larger than that of $5\,n + 10$ (n represents the sample size). These results indicated the absence of publication bias in the collected literature and confirm the high reliability of the meta-analysis findings.

3.3. *Analysis of the influence factors of biochar addition on maize yield and PFPN*

3.3.1. *Experimental regions*

Maize yield and PFPN response to biochar varied by region (Fig. 3a and Fig. 3c). In the case of yield, the yield-enhancing effects of biochar exhibited a declining trend with the experimental duration increase, and the minimum yield increase was 6.93 % (95 % CI = 4.61 %-9.29 %). Among the different regions, the highest yield increase was observed in South China (mean 88.14 %), followed by Northwest and Southwest China, while the lowest in Central China (mean 6.53 %). Meanwhile, the yield-increasing effects showed an initial decreasing and then increasing with the increase of average annual precipitation (AAP), and reached the highest increase (mean 22.56 %) at AAP $\geq$ 800 mm; the yield-increasing effects showed a fluctuating and increasing trend with the increase of average annual temperature (AAT), and reached the greatest increase (mean 29.97 %) at AAT $\geq$ 16℃. In the case of PFPN, biochar addition had the most significant improvement on PFPN in Northwest China (mean 25.02 %, 95 % CI = 18.16 %-32.28 %), whereas no statistically significant effects were observed in other regions. Different from the yield, the PFPN growth rate showed a first decreasing, second increasing and then decreasing trend with increasing AAP, and first increasing and then decreasing trend with increasing experimental duration and AAT, and the maximum increase in PFPN (mean 22.31 %-31.17 %) was reached at AAP < 200 mm, experimental duration of 2 a, and AAT of 8–12°C.

In addition, the effects of biochar on maize yield and PFPN varied significantly among experimental year (Fig. 3b and d). The increasing effects of biochar on both maize yield and PFPN showed a fluctuating and increasing trend with the experimental year progressed. Further analysis revealed that biochar application substantially increased maize yield (mean 29.88 %, 95 % CI = 14.60 %-47.19 %). For PFPN, the point estimate of the increase was similarly high (mean 39.19 %); however, the corresponding 95 % confidence interval was wide and included zero (-1.73 %-97.13 %), indicating that this effect was not statistically significant. In conclusion, biochar application has the most significant promoting effects on maize yield and PFPN in regions with more recent experimental year, lower precipitation or moderate temperature.

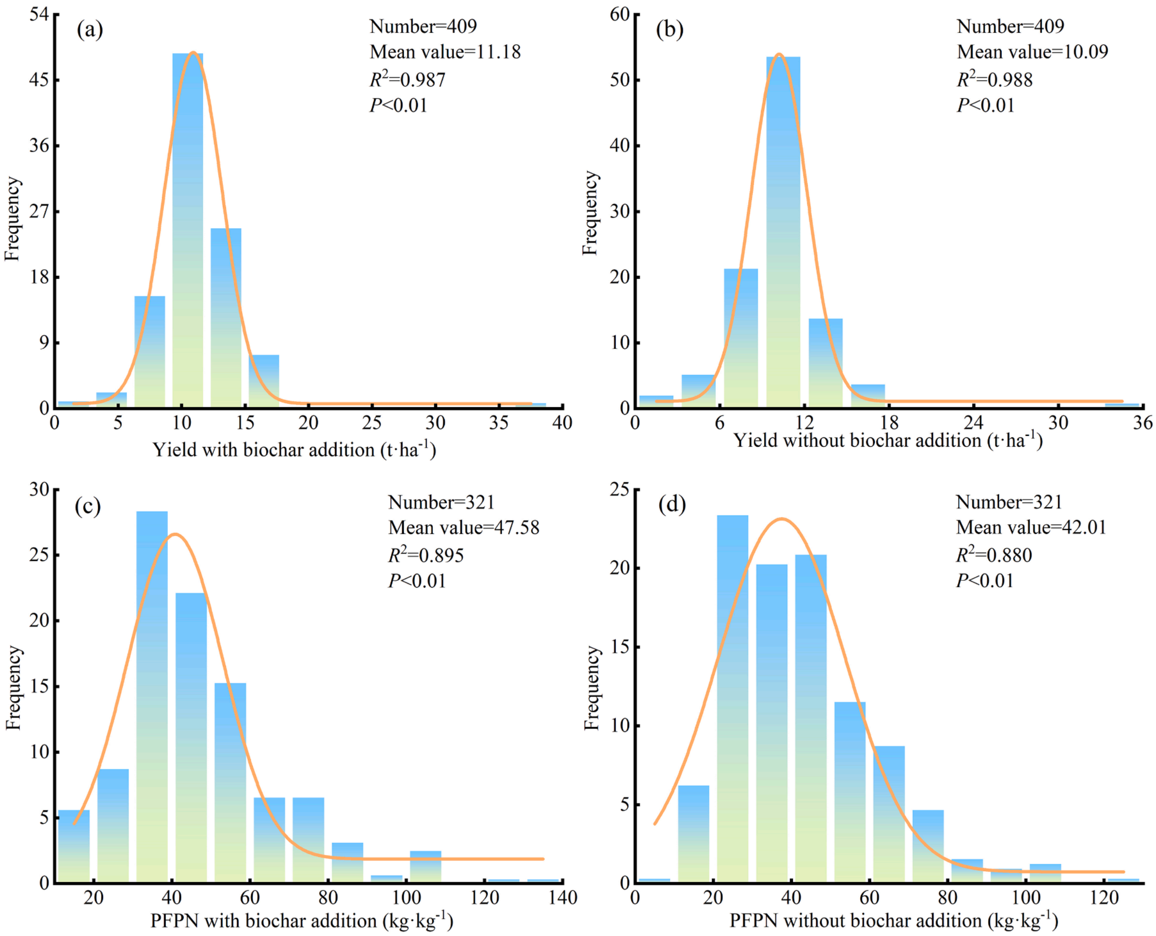

Fig. 1. Frequency distribution of maize yield (a and b) and PFPN (c and d) with and without biochar addition.

3.3.2. *Field management*

3.3.2.1. Biochar factors. Maize yield and PFPN response after biochar addition were affected by biochar characteristics, biochar application duration and biochar application amount (Fig. 4). The application of firewood biochar had the most significant enhancement effects on maize yield and PFPN, both amounting to 25.71 % (95 % CI = 18.27 %-33.62 %), whereas cotton straw biochar had the lowest increase, with average yield and PFPN only 5.21 % and 5.27 %. Moreover, the yield-increasing effects of biochar application on maize increased with increasing pyrolysis temperature (PT), reaching an average yield increase of 20.61 % when the PT was $\geq$ 475℃. In contrast, the PFPN growth rate first increased and then decreased with increasing PT and peaked at PT of 400–475°C (mean 25.71 %, 95 % CI = 18.27 %-33.62 %), followed by $\geq$ 475°C, while the growth effect weakened at $<$ 400°C (mean 7.16 %). In addition, the maize yield and PFPN growth rates tended to first decrease and then increase with increasing biochar pH, and reached the minimum at pH 9–10. Biochar with C/N of 60–70 and C/N $\geq$ 70 were more effective in enhancing yield (mean 11.29 % and 10.64 %) and PFPN (mean 19.22 % and 14.86 %) than biochar with C/N $<$ 60.

Further analysis showed that the increase in maize yield upon biochar application first decreased and then increased with increasing biochar application duration. Specifically, the maize yield increases reached 13.87 % (95 % CI = 10.25 %-17.60 %) and 12.97 % (95 % CI = 8.07 %-18.09 %) with the application duration of 1 a and 2 a. However, extending the application duration to 3 a reduced the yield increase to 8.04 % (95 % CI = 5.76 %-10.37 %). Particularly, when applied for $\geq$ 4 a, the yield-increasing effects of biochar application was again enhanced with an average yield increase of 10.22 %. This may be due to the fact which biochar improved the original soil environment, thus providing more favorable conditions for maize production (Barros et al., 2021). For PFPN, the improvement could reach 21.18 % (95 % CI = 13.56 %-29.31 %) when applied for 2 a, but was no significant difference when applied for 1 a and $\geq$ 4 a. Furthermore, biochar application amount significantly influenced crop productivity enhancement. With the biochar application amount increase, the average yield and PFPN increase rates maintained at 6.03 %-19.60 % and 11.04 %-23.02 %, respectively.

3.3.2.2. Planting factors. Maize yield and PFPN response to biochar varied with planting factors such as maize variety, planting density (PD), and irrigation condition (IC) (Fig. 5). Among the maize varieties, Liangyu 777 had the highest yield increase (mean 14.79 %, 95 % CI = 10.14 %-19.63 %), followed by Ximeng 6, while Suyu 29 had the lowest. In terms of PFPN, Dafeng 30 had the most prominent increase in maize PFPN (mean 86.56 %, 95 % CI = 73.68 %-100.41 %). Meanwhile, with the increase of PD, the maize yield increase rate showed an increasing trend, while PFPN showed initial decreasing and then increasing. Among them, the yield-increasing effects were significantly elevated when PD was $>$ 50,000 plants·ha^{-1}, but the positive effects of further increasing PD thereafter gradually leveled off. It is worth noting that although irrigation conditions contributed to maize yield accumulation, the yield-increasing effects did not show significant differences among irrigation categories. In contrast, the PFPN increase rate under rainfed condition was significantly higher than that under irrigated condition, with a mean enhancement of 17.62 %.

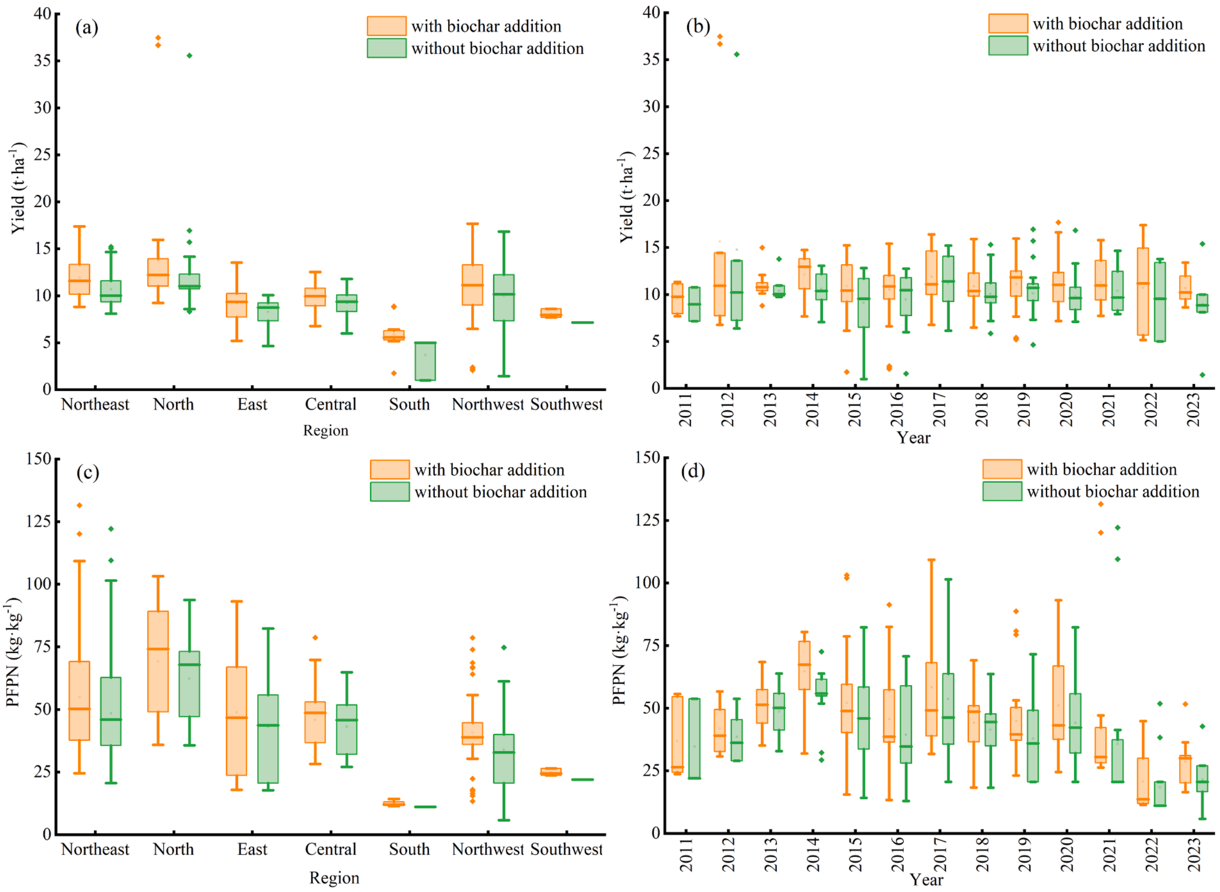

Fig. 2. Temporal and spatial changes of maize yield (a and b) and PFPN (c and d) in China. Region and year represent the region of the experiment and the year of the experiment, respectively.

Table 2
The comprehensive effect of biochar addition on corn yield and PFPN.

Item	Model	Increase rate	95 % Confidence interval		Z	P	Q_t	P_Q	Rosenthal	
			Lower limit	Upper limit						
Yield	Random effect model	12.73	10.49	15.02	11.71	0.000	117527.38	0.000	5456215	2055
PFPN	Random effect model	15.76	13.32	18.26	13.46	0.000	14388.31	0.000	762945	1650

Note: *PFPN* represents the partial factor productivity of nitrogen for maize; *Z* is the statistic of effect size; *P* is the significance value of *Z*; Q_t is the statistic of heterogeneity; P_Q is the significance value of publication bias.

3.3.3. *Soil environment*

Different soil environments significantly influenced the yield and PFPN effects of biochar application on maize (Fig. 6). Regarding soil texture, biochar had the highest yield-increasing effects in clay (C) (mean 21.75 %, 95 % CI = 13.92 %-30.12 %) and the strongest effects in silty loam (SL) (mean 29.59 %, 95 % CI = 12.00 %-49.94 %). Regarding soil types, the yield-increasing effects were the most prominent in red soil (RS) (mean 56.55 %) and moist soil (MoS) (mean 45.64 %), followed by loess (LS). Regarding soil physical properties, the maize yield increase showed a gradual increasing trend with increasing soil bulk density (BD), while PFPN showed an initial increase and then decrease. Particularly, the maximum positive effects of both yield and PFPN consistently occurred at BD $> 1.3\ \mathrm{g{\cdot}cm^{-3}}$. In addition, with increasing soil pH, the maize yield and PFPN responses to biochar application showed initial decreasing and then increasing trend. In particular, the maximum yield enhancement (mean 44.06 %) occurred under acidic conditions (pH < 8), whereas the maximum PFPN improvement (mean 22.44 %) appeared under alkaline conditions (pH ≥ 8).

Further analysis found that the effect patterns of different soil nutrient indexes on maize yield and PFPN were also significantly different. Specifically, with the increase of SOM content, the yield-increasing effects of maize gradually weakened, while the PFPN-increasing effects gradually increased. Among them, when the soil organic matter (SOM) was $< 10\ \mathrm{g{\cdot}kg^{-1}}$, the maize yield increase was the highest 28.95 % (95 % CI = 9.49 %-51.88 %), and the PFPN increase was the lowest 10.88 % (95 % CI = 5.36 %-16.68 %). With the increase of Alk N content, the maize yield increase tended to first increase and then decrease, and reached the maximum (mean 39.26 %) at the soil alkaline nitrogen (Alk N) content of 80–120 $\mathrm{mg{\cdot}kg^{-1}}$, while the PFPN increase was the opposite. Meanwhile, the yield-increasing effect of maize reached the highest (mean 15.65 %, 95 % CI = −1.29 %-35.51 %) at the soil organic carbon (SOC) content of 10–20 $\mathrm{g{\cdot}kg^{-1}}$, while the improvement effect of PFPN also reached the maximum (mean 31.08 %, 95 % CI = 5.76 %-62.47 %) within this range. Furthermore, the increase in maize yield and PFPN upon biochar application showed first decreasing and then increasing with the increase of soil total nitrogen (TN) content, and the mean positive effects of both reached the lowest

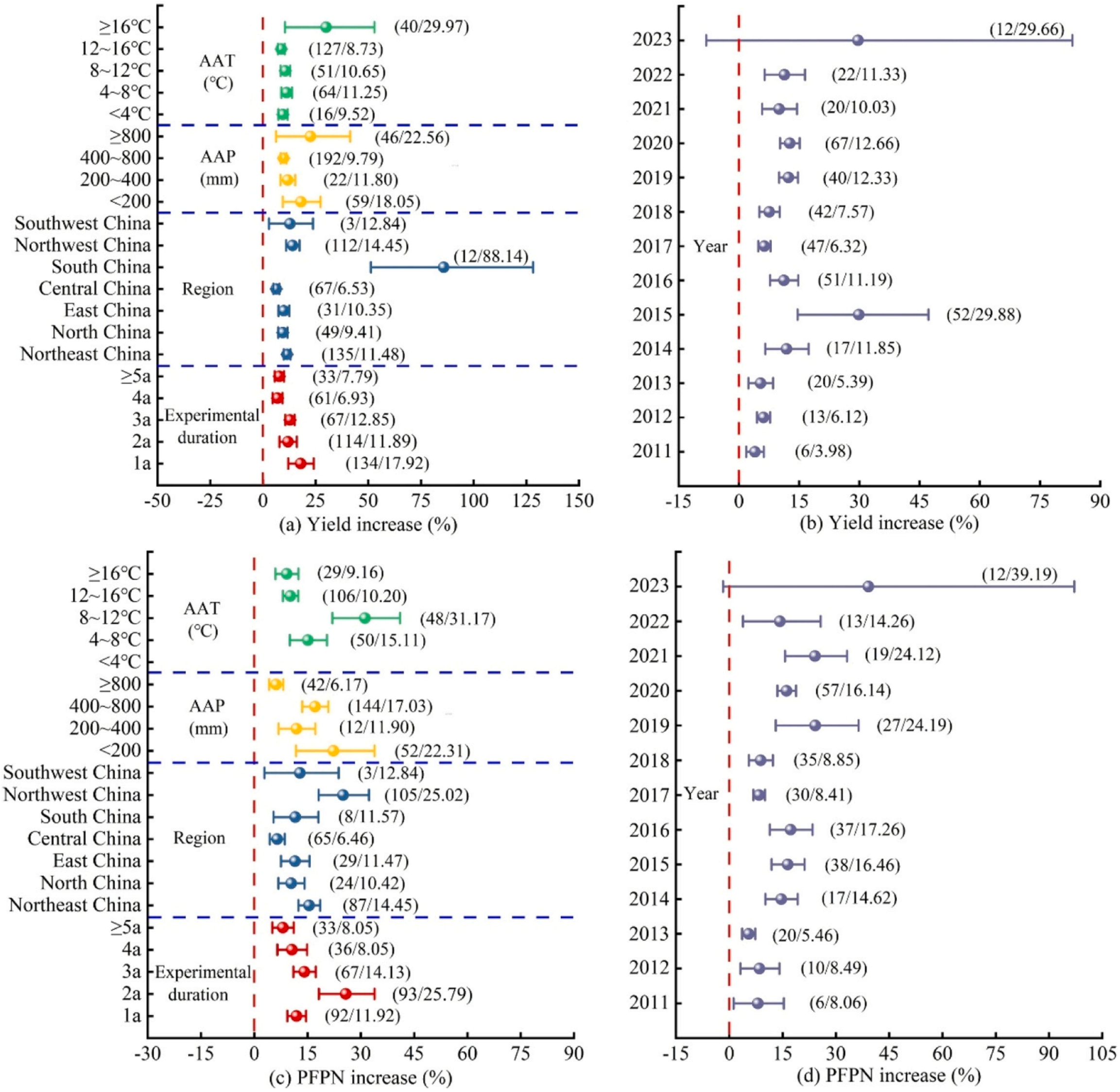

Fig. 3. Effect of region and year on maize yield (a and b) and PFPN (c and d). Error lines and dots indicate 95 % confidence intervals and average improvement rates, respectively, and the numbers to the right of the error lines indicate the number of samples in the corresponding subgroups and the improvement rates. AAP, AAT, region and year represent average annual precipitation, average annual temperature, the region of the experiment, and the year of the experiment, respectively.

values when the TN content ranged from 0.8 to 1.1 g·kg^{-1}, which were 8.44 % and 9.02 %, respectively.

In addition, in terms of the influence of soil available nutrients, the yield-increasing effects of maize gradually decreased with increasing soil available nitrogen (AN) content. In contrast, the improvement effects of PFPN gradually increased and reached the maximum value at AN ≥ 60 mg·kg^{-1} (mean 48.13 %, 95 % CI = 32.57 %-65.51 %). However, the effects of soil available phosphorus (AP) content on maize yield and PFPN improvement effects showed an opposite trend, and the differences in effects among different AP contents were not significant. For soil available potassium (AK), the maximum yield-increasing effects of maize (mean 19.66 %) occurred when the AK content was < 120 mg·kg^{-1}, while the maximum increase effect of PFPN (mean 22.98 %) occurred when the AK content was ≥ 160 mg·kg^{-1}.

3.4. *Importance of different factors on maize yield and PFPN changes with biochar addition*

To find the main influences on maize yield and PFPN under biochar addition conditions, two machine learning models, Random Forest (RF) and Gradient Boosting Machine (GBM), were used to assess the importance of 25 variables (X1-X25 represent experimental duration, experimental region, AAP, AAT, experimental year, biochar feedstock, biochar PT, biochar pH, biochar C/N, biochar application duration, biochar application amount, maize variety, PD, IC, soil texture, soil type, BD, pH, SOM, Alk N, SOC, TN, AN, AP, and AK, respectively.) on the variation of maize yield and PFPN (Fig. 7). For maize yield variation, in the RF model, the variable X11 (16.72 %) had the highest importance as measured by the %IncMSE indicator, indicating that it played a central role in explaining yield variation, followed by X17 (10.70 %), X4 (9.24 %), X5 (8.83 %) and X22 (8.39 %). In the GBM model, the top 2 variable importance rankings as measured by the rel.inf indicator were X4 (17.94 %) and X11 (17.58 %), followed by X3 (10.28 %), X5 (9.40 %) and X17 (7.94 %). Similarly, for PFPN, the 5 most important variables in the RF model were X3 (13.09 %), X15 (11.04 %), X18 (10.05 %), X1 (9.43 %), and X11 (9.17 %). In the GBM model, the top 5 variables were X3 (34.90 %), X15 (17.55 %), X1 (7.45 %), X22 (6.32 %), and X7 (5.76 %).

3.5. *Multiple factors analysis to seek the optimal model*

To construct parsimonious multivariate models, we selected the top

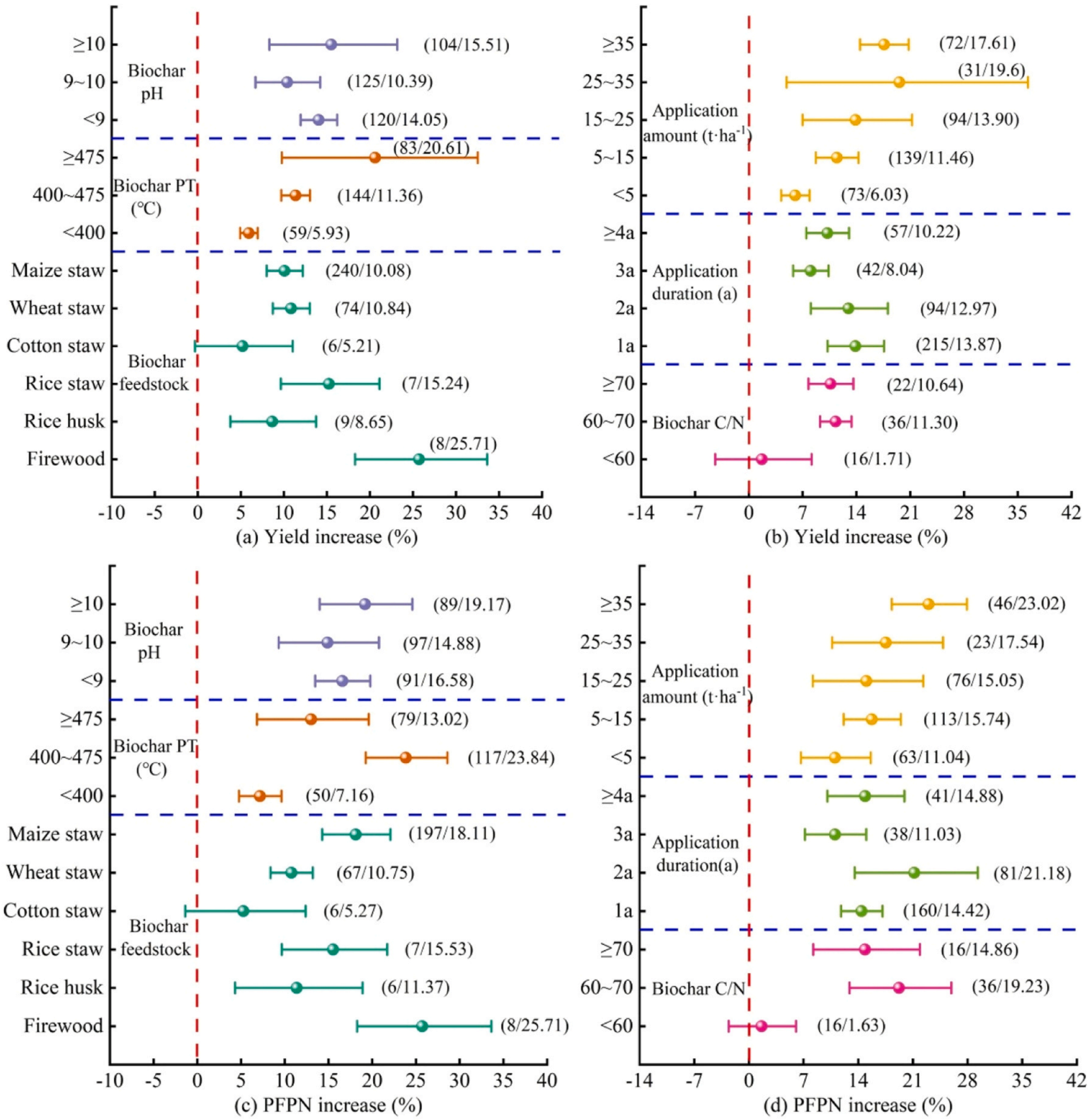

Fig. 4. Effect of biochar on maize yield (a and b) and PFPN (c and d). Error lines and dots indicate 95 % confidence intervals and average improvement rates, respectively, and the numbers to the right of the error lines indicate the number of samples in the corresponding subgroups and the improvement rates. Biochar PT represents biochar pyrolysis temperature.

5 predictive variables from the RF and GBM models, respectively, and took the union of these variables as the candidate variable set for subsequent model optimization. Therefore, the factors affecting the yield change of maize include X3, X4, X5, X11, X17 and X22, and the factors affecting the change of PFPN include X1, X3, X7, X11, X15, X18 and X22. As can be seen in Table 3, the change in yield of the model Yield~1 + X4 + X5 + X11 + X22 was the optimal model with Aicc value and weight of −285.774 and 0.807, respectively. Similarly, in PFPN variation, model PFPN~1 + X1 + X11 + X15 + X18 + X22 was the optimal model with the lowest Aicc value and weight of 0.807. In conclusion, the AAP, experimental year, biochar application amount and soil TN were the important factors affecting the maize yield, while the experimental duration, biochar application amount, soil textures, soil pH and soil TN were the main factors affecting PFPN.

4. Discussion

4.1. Effects of region and year on maize yield and PFPN

The research regions and years are critical for crop growth and water-fertilizer resource utilization, and their differences directly determine the stability and generalizability of crop yields, nutrient uptake efficiency, and environmental effects. Carkner and Entz (2017) found that geographic location was the dominant factor influencing the spatial variability of crop yield by analyzing soybean yield data from 10 experimental regions and years, and its contribution to the total yield variability was as high as 72.40 %. Furthermore, Waheed et al. (2025) further demonstrated that the addition of biochar to nutrient-deficient soils could significantly enhance crop productivity with an average yield increase of up to 30 %, which was consistent with the results of this study. In this study, we founded that there were significant regional differences in the yield-increasing effect of biochar, with the highest yield increase (mean 88.14 %) in South China. This may be closely

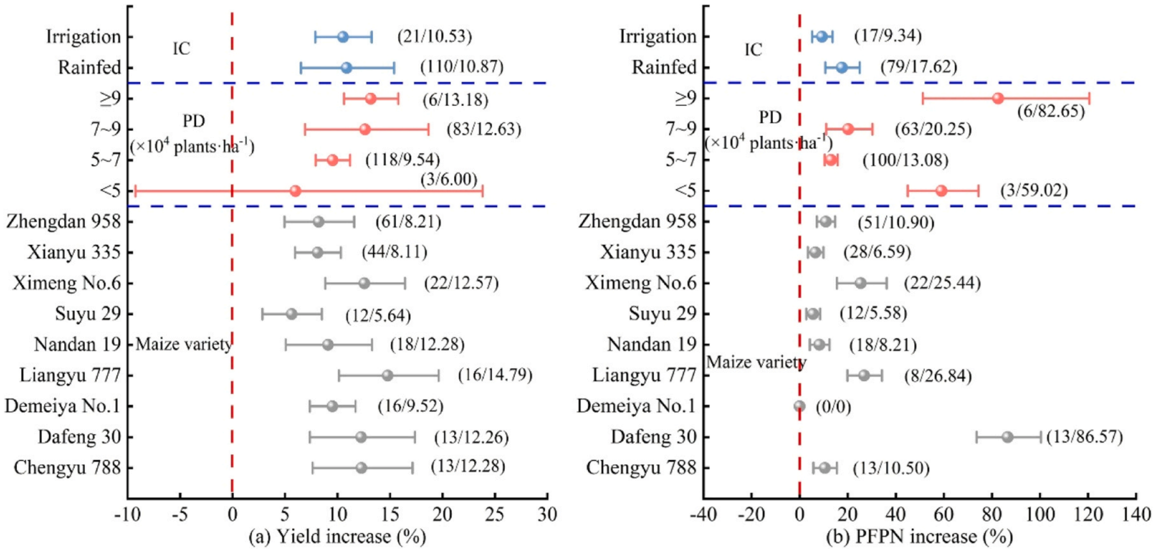

Fig. 5. Effect of planting factors on maize yield (a) and PFPN (b). Error lines and dots indicate 95 % confidence intervals and average improvement rates, respectively, and the numbers to the right of the error lines indicate the number of samples in the corresponding subgroups and the improvement rates. PD and IC represent planting density and irrigation condition, respectively.

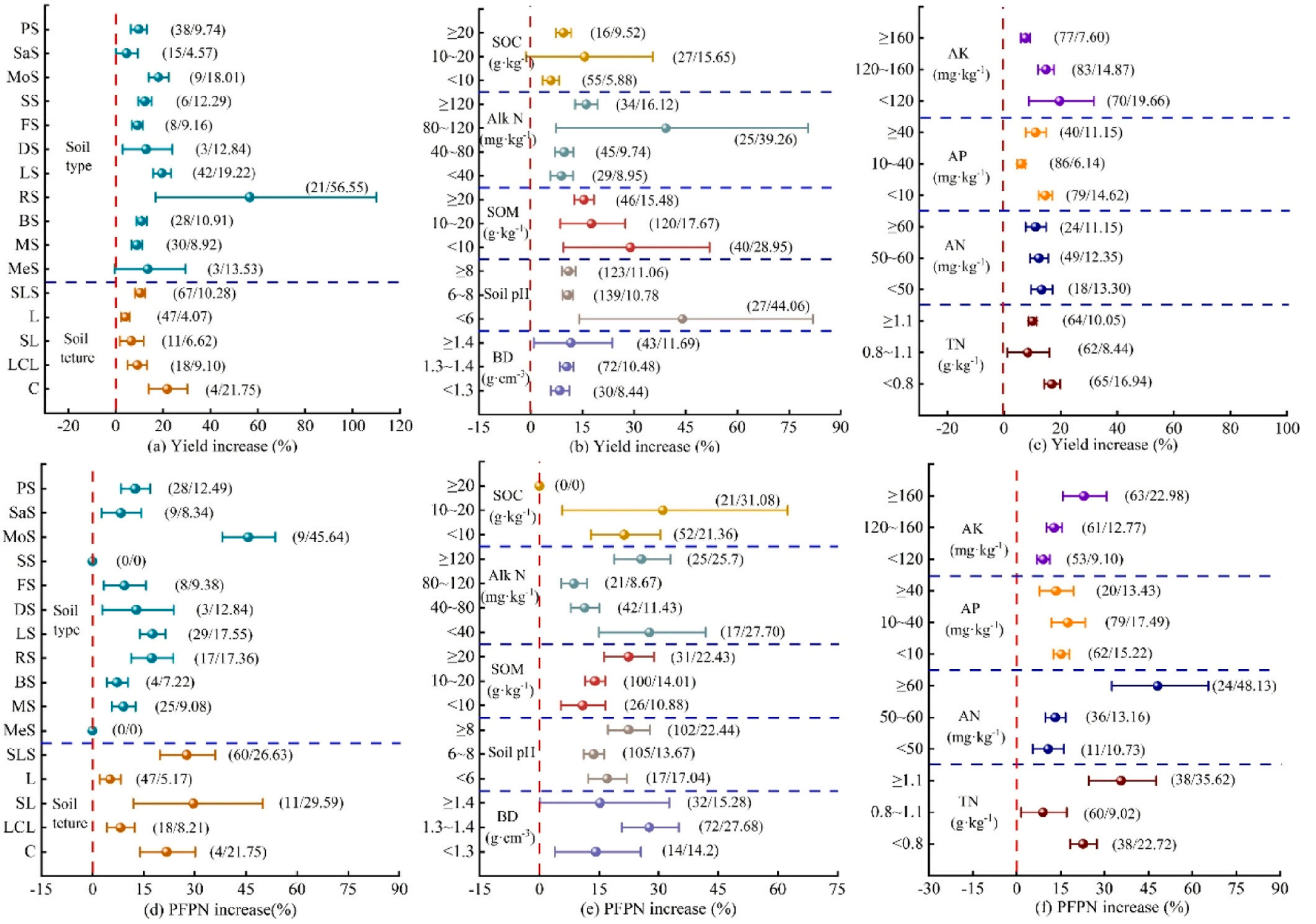

Fig. 6. Effect of soil environment on maize yield (a, b and c) and PFPN (d, e and f). Error lines and dots indicate 95 % confidence intervals and average improvement rates, respectively, and the numbers to the right of the error lines indicate the number of samples in the corresponding subgroups and the improvement rates. BD, SOM, Alk N, SOC, TN, AN, AP, and AK represent soil bulk density, soil organic matter, soil alkaline nitrogen, soil organic carbon, soil total nitrogen, soil available nitrogen, soil available phosphorus, and soil available potassium, respectively.

related to the soil and climate conditions in South China. Specifically, the soil in this region is dominated by red soil with relatively low

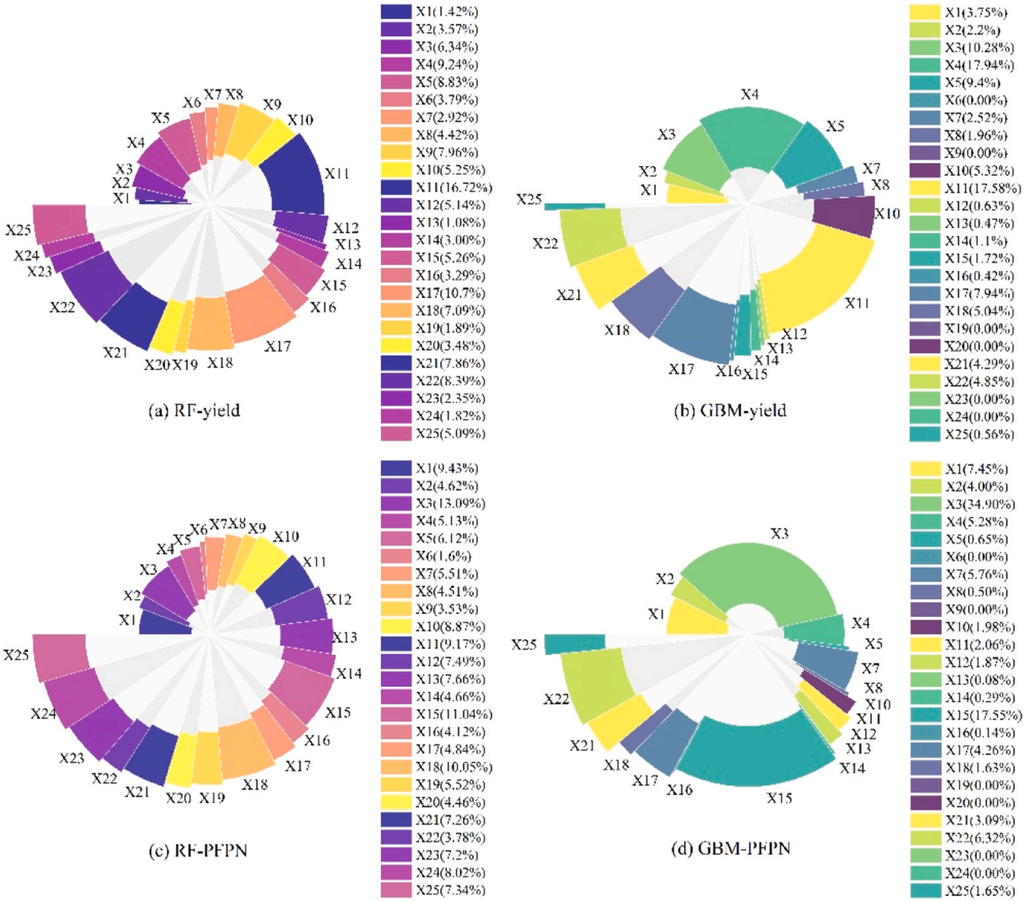
(a) RF-yield
(b) GBM-yield
(c) RF-PFPN
(d) GBM-PFPN

Fig. 7. Ranking of importance of factors influencing corn yield and PFPN. Note: (a-b) indicates the importance ranking of factors affecting corn yield change in random forest model and GMB model respectively; (c-d) represents the importance ranking of influencing factors of maize PFPN change in random forest model and GMB model, respectively. X1-X25 represent experimental duration, experimental region, AAP, AAT, experimental year, biochar feedstock, biochar PT, biochar pH, biochar C/N, biochar application duration, biochar application amount, maize variety, PD, IC, soil texture, soil type, BD, pH, SOM, Alk N, SOC, TN, AN, AP, and AK, respectively.

Table 3
Multi-factor optimization model.

Item	Yield	PFPN
Optimal model	Yield~1 + X4 + X5 + X11 + X22	PFPN ~ 1 + X1 + X11 + X15 + X18 + X22
Aicc	-285.774	-249.114
weights	0.807	0.872

Note: X1, X4, X5, X11, X15, X18 and X22 represent experimental duration, AAT, experimental year, biochar application amount, soil texture, soil pH, and soil TN, respectively.

fertility, and the application of biochar can significantly improve the soil structure and promote the growth and development of plants. Secondly, adequate annual precipitation and long sunshine time in this region are conducive to the long-term availability of biochar in soil, thus significantly enhancing its yield-increasing effects. Additionally, it has also been pointed out that soil properties and climatic conditions in different regions also affect the efficiency of fertilizer uptake and utilization (Zhu et al., 2024). In this study, the positive effects of biochar on PFPN were most significant in Northwest China. This indicates that biochar can fully play multiple roles in this region, including soil improvement, root promotion, microbial activation, and enhancement of nitrogen transformation and utilization efficiency, thus increasing PFPN (Shi et al., 2024).

Precipitation and temperature are pivotal climatic factors regulating agricultural production (Li and Chang, 2020), which synergistically affect the effectiveness of water-fertilizer resources and the nitrogen mineralization processes, forming an intricate response mechanism for agricultural production (Kay et al., 2006). In this study, the increasing effects of biochar on maize yield varied significantly across climatic conditions. The yield enhancement effects of biochar reached the highest (mean 22.56 %) when the average annual precipitation was $\geq$ 800 mm. It may be that the porous structure and surface properties of biochar can effectively improve the stability of soil aggregates and enhance the ability of water and fertilizer retention, thereby promoting crop growth more efficiently under humid climatic conditions. In addition to this, the yield-increasing effects of maize showed a fluctuating and increasing trend with the increase of annual average temperature, which was consistent with the research results of Yang et al. (2021) on spring wheat. However, the enhancement effects of biochar on maize PFPN were prominent in regions with average annual precipitation $<$ 200 mm and average annual temperature of 8–12°C. There are two possible reasons for the different results: on the one hand, supersaturated soil moisture will exacerbate nitrogen fertilizer leaching losses in regions with excessive precipitation; on the other hand, extreme temperatures (high or low temperature) can weaken or inhibit soil microbial activity and reduce the rate of organic matter mineralization, thus limiting nitrogen effectiveness (Barros et al., 2021). Furthermore, this study found that the effect sizes of biochar on maize yield and PFPN fluctuated with the experimental years, with the average effect sizes being higher in recent years. This temporal dynamic characteristic may reflect the combined differences in climatic conditions, management measures, and variety replacements among different years, creating a differentiated background of biochar responses and generating a stronger synergy between biochar and modern high-yield and efficient agricultural systems, rather than a single-year effect. Since the 1980s, fertilizer application per unit of arable land in China has continued to increase, but the fertilizer utilization rate of main grain crops has only remained at the level of 42.60 %, resulting in the accumulation of large amounts of nutrient residues in cultivated land. Against this background, biochar, with its high specific surface area and rich functional group properties, can form a “nutrient slow-release reservoir” in the soil, reducing nitrogen volatilization and leaching losses while effectively regulating nutrient release dynamics (Zhou et al., 2021, Waheed et al., 2025). Notably, this characteristic can not only enhance the yield accumulation of crops in the current season, but also improve the soil nutrient pool capacity, extend the effective nitrogen supply cycle, and realize the continuous improvement of nitrogen utilization efficiency.

4.2. Effects of field management on maize yield and PFPN

Biochar addition, as an efficient water-saving and environmentally friendly soil improvement measures in agriculture, represents not only a crucial approach for agricultural green transition and global carbon neutrality, but also provides a novel solution for addressing food security and sustainable agriculture (Zhang et al., 2021). Biochar properties are mainly dependent on factors such as raw materials and production processes (Tag et al., 2016), and there are significant differences in the effects of different properties on crop yield enhancement and efficiency improvement. Notably, raw materials selection emerges as the primary factor influencing crop yield responses to biochar application. This study revealed that firewood biochar significantly outperformed straw biochar in enhancing maize yield and PFPN. The superior performance is primarily attributed to differences in pore structure characteristics. Compared to straw biochar, firewood biochar possesses a more developed porous structure that facilitates efficient adsorption of soil nutrients (e.g., NH_4^+ and NO_3^-), thereby substantially improving soil fertility and its yield and efficiency enhancement effects (Kim et al., 2014). Furthermore, existing studies suggest that pyrolysis temperature serves not only as a critical parameter in biochar carbonization processes but also as a key indicator of its stability. Elevated pyrolysis temperatures can significantly enhance biochar’s specific surface area and pore structure (Xiang et al., 2021), thereby improving soil water-holding capacity and nutrient retention (Wang et al., 2020), which ultimately promotes crop growth. In this study, the promotional effects of biochar on maize yield exhibited a positive correlation with pyrolysis temperature, peaking at temperatures $\geq 475^\circ C$. This finding differs from the results reported by He et al. (2025), who observed maximum crop yield within the 401–550°C pyrolysis range. In contrast, the enhancement effects of biochar on maize PFPN showed a tendency of first increasing and then decreasing with increasing pyrolysis temperature, and reached the maximum value (mean 25.71 %) at pyrolysis temperatures of 400–475°C. The results indicated that the biochar with appropriate pyrolysis temperature could optimize the soil nitrogen supply environment, promote microbial activity, and enhance nitrogen adsorption capacity. However, the biochar with excessively high pyrolysis temperature may increase nitrogen fixation or reduce nitrogen availability due to the increase of its own stability and the slowing down of the degradation rate to weaken the stimulation of microorganisms (Li et al., 2025). Biochar pH and C/N content also affected crop yield and water-fertilizer resource use efficiency. Meanwhile, the yield-enhancing and efficiency-improving effects of biochar on maize were most significant at biochar pH of 9–10 and C/N ratio of 60–70. These findings suggest that biochar may directly affect crop growth by regulating soil pH (Singh et al., 2021), or trigger microorganisms to compete with the crop for nitrogen by altering the soil C/N ratio (high or low C/N), inhibiting the uptake of effective nitrogen by the crop and its normal growth (Liang et al., 2010). In addition, this study also found that the optimal effects on maize yield enhancement were achieved when biochar application duration was 1a and the biochar application amount was 25–35 $t \cdot ha^{-1}$, demonstrating that biochar can be used as a carrier for the slow release of fertilizers and play a complementary and synergistic role with fertilizers. However, it is worth noting that the number of samples with biochar application duration and amount in this range were 215 and 31, respectively, which were much higher or lower than the other sample sizes. This significant imbalance in sample size introduces considerable uncertainty to our conclusions regarding their effects on maize yield enhancement and efficiency improvement. Therefore, future research urgently requires specifically designed, long-term, multi-site field trials. Under a balanced sampling framework, such trials should systematically validate these potential optimal application ranges and elucidate the underlying "biochar-fertilizer-soil" interaction mechanisms, thereby establishing a solid scientific foundation for formulating precise agronomic strategies.

Similarly, maize variety, planting density and irrigation conditions all had significant effects on yield enhancement and PFPN improvement in biochar-applied maize. Among the maize varieties, Liangyu 777 showed the most significant yield enhancement effects, while Dafeng 30 showed the best performance PFPN improvement. These differences likely stem from distinct genetic characteristics, morphological growth patterns, and physiological metabolic traits of maize varieties. Additionally, Koffi et al. (2022) demonstrated that planting density regulates crop growth and development by modulating canopy architecture and resource utilization efficiency, while optimized density achieves both high yield and resource use efficiency. In our study, similar results were obtained for biochar-applied maize, that is, both yield and PFPN were highest at planting densities $\geq 90{,}000$ $plants \cdot ha^{-1}$. These results further validate that high-density planting combined with biochar application can enhance the photosynthetic efficiency of crop population (Li et al., 2025), optimize crop growth coordination, and promote the synergistic improvement of yield and PFPN. Meanwhile, this study found that the yield-increasing and PFPN-improving effects of biochar under irrigation conditions were slightly lower than under rainfed conditions. This difference may be related to the biochar mechanism dominated by water conditions. Under rainfed conditions, water supply is a key limiting factor for crop growth. Biochar enhances water holding capacity by improving soil pore structure, directly alleviating water limitation, and thereby promoting nutrient mineralization, migration and root absorption, thus demonstrating a more significant effect on increasing yield and improving efficiency. Under irrigation conditions, water is no longer the main limiting factor, and the water-improving effect of biochar weakens. Its synergistic mechanism may shift more towards soil structure optimization or nutrient slow-release, etc. However, these effects were not fully manifested in the index system of this study.

4.3. Effects of soil environment on maize yield and PFPN

Under the background of sustainable agricultural development and global food security challenges, the biochar addition, as an efficient and long-term stable carbon management strategy, contributes to the construction of an efficient and sustainable soil environment (Bakshi et al., 2018). Research demonstrates that the soil environment is a central factor in agricultural production, and its physicochemical properties and biological characteristics directly affect crop growth and development, and resource utilization efficiency (Uddin et al., 2025). The results of this study also demonstrated that the differences in maize yield and PFPN response to biochar were related to the soil environment, such as soil texture, physical properties, and nutrients. In terms of soil texture, the effects of soil texture on maize yield and PFPN were more significant. Among them, the C showed the strongest yield-enhancing effect, while the SL exhibited the highest PFPN improvement, indicating differential regulatory mechanisms of biochar across soil textures. Furthermore, the RS had the most significant yield-increasing effects on maize in this study, while the MoS favored PFPN enhancement. These may be determined by the soil properties of RS and MoS and their synergistic effect with biochar together. Similarly, the influence of soil physical and chemical properties on the biochar effect has certain regularity (Bekchanova et al., 2024). Based on meta-analysis, Jiang et al. (2025) concluded that the yield-increasing effects of maize first increased and then decreased with the increase of BD, and the yield-enhancing effects were the greatest at 1.2–1.4 $g\cdot cm^{-3}$ (mean 58.01 %).

However, our study found that the maize yield-increasing effects tended to increase with the increase of BD, while PFPN first increased and then decreased. This result suggests to some extent that moderately increasing soil density may benefit to the improvement of maize yield, while excessive density could inhibit nitrogen utilization efficiency. In addition, it has also been shown that soil pH is the primary indicator of soil acidity and alkalinity, which can directly affect soil nutrient effectiveness. Moreover, both excessively high and low soil pH will restrict crop absorption of essential nutrients, thereby affecting crop growth and yield. Similarly, the effects of soil pH on yield and PFPN of biochar-applied maize in this study were characterized by nonlinearity. Among them, the yield-increasing effects of biochar were the strongest at $pH < 6$, while the PFPN-improving effects of biochar were the most significant at $pH \geq 8$. These results indicated that biochar has a moderating effect on both acidic and alkaline soils (Fernandez-Ugalde et al., 2017). In acidic soils, the alkaline properties of biochar can effectively neutralize soil acidity and elevate pH to the appropriate range for crop growth (Nkoh et al., 2021). In alkaline soils, biochar can enhance soil nitrogen retention through surface negative charge and pore adsorption of NH_4^+, thereby improving soil fertility and crop nitrogen uptake efficiency (Fiorentino et al., 2019).

Soil nutrients refer to the nutrient elements in soil that can be directly absorbed by plant roots or indirectly absorbed after transformation, serving as a key indicator to measure soil fertility. It is notable that there is an interaction between soil nutrient changes and biochar effect (Liu et al., 2022). In this study, the increase rate of maize yield exhibited an inverse trend with increasing SOM content, whereas the improvement rate of PFPN showed a positive correlation with SOM content. This indicates that with the increase of SOM content, the soil's inherent nutrient supply capacity improves, potentially shifting yield-limiting factors from soil nutrients to other environmental factors (e.g., light, moisture and temperature), thereby attenuating biochar's yield-enhancing effects. Nevertheless, biochar retains its capacity to optimize nutrient adsorption and retention (Lima et al., 2018), thereby sustaining continuous improvement in PFPN. Similarly, the influence of Alk N content on maize productivity followed a trend analogous to that of SOM. The yield-enhancing and efficiency-enhancing effects of biochar peaked at Alka N content of 80–120 $mg\cdot kg^{-1}$ and < 40 $mg\cdot kg^{-1}$, respectively, indicating that an appropriate soil N supply can optimize the regulatory effects of biochar. Conversely, both maize yield and PFPN response to biochar peaked at SOC content of 10–20 $g\cdot kg^{-1}$, further validating the interactive effects between soil nutrients and biochar. Additionally, Hossain et al. (2020) pointed out that biochar was able to influence the effectiveness of N and P in soil by immobilizing soil minerals. This study found that biochar had the optimum effects on yield-enhancing and efficiency-improving in soils with TN content of 0.8–1.1 $g\cdot kg^{-1}$. However, after the AN content increased, the yield enhancement effects of maize decreased, while the PFPN improvement effects increased. This suggests that under sufficient soil nitrogen supply, biochar primarily enhances yield by improving nitrogen use efficiency rather than through direct N supplementation. Meanwhile, the influence trends of AP and AK contents on maize productivity are opposite. Among them, the maize yield enhancement effects decreased with the increase of AK content, while the PFPN improvement effects gradually increased. This may be attributed to the high K content altering the soil fertility and nutrient balance (Wang et al., 2014), resulting in a trade-off effect between biochar's impacts on yield and PFPN. In summary, crop yield and nitrogen utilization efficiency can be effectively enhanced by the judicious application of biochar to optimize soil environmental factors. These findings can provide a scientific basis and practical guidance for the precision application of biochar in agricultural production.

5. Conclusion

This study integrated meta-analysis with machine learning to systematically evaluate the enhancing effects of biochar on maize yield and the partial factor productivity of nitrogen (PFPN) in China and to identify their key drivers. The results show that biochar application increased maize yield and PFPN by an average of 12.73 % and 15.76 %, respectively, with the effect sizes exhibiting significant spatial heterogeneity and environmental dependence. Further analysis revealed that maize yield improvement was primarily regulated by annual average temperature, experimental year, biochar application amount, and soil total nitrogen, while PFPN enhancement depended more on experimental duration, biochar application amount, soil texture, soil pH, and soil total nitrogen. Based on these findings, to achieve the maximum agronomic benefits of biochar, regional differentiated strategies should be adopted. In the high-temperature and high-humidity South China region, emphasis should be placed on increasing yield, while in the arid and low-precipitation Northwest region, it should be prioritized to enhance nitrogen fertilizer utilization efficiency. However, there are still significant challenges in translating the research results into practice. The key factors and their interactions identified by machine learning need to be verified through long-term field experiments. Meanwhile, the economic feasibility, agronomic applicability, and long-term environmental effects of biochar still need to be systematically evaluated. Therefore, future research should focus on establishing a precise biochar regulation system based on climatic, soil, and management conditions, and through multi-year and multi-site empirical studies, develop regionally adapted application schemes. This will provide a reliable scientific basis for enhancing the sustainable productivity of maize systems and ensuring regional and global food security.

CRediT authorship contribution statement

Xiaotao Hu: Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Yakun Wang:** Methodology, Investigation, Funding acquisition. **Yang You:** Visualization, Validation, Resources. **Hang Qin:** Supervision, Software. **Tianqi Wang:** Investigation, Formal analysis, Data curation. **Rongrong Tian:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xiaotao hu reports financial support was provided by the National Key Research and Development Project of China (2023YFD2301103). Reports a relationship with that includes:. Has patent pending to. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We appreciate the National Key Research and Development Project of China (2023YFD2301103) for providing a grant for this study. And we also would like to thank the anonymous reviewers for their valuable comments on the manuscript.

Data Availability

Data will be made available on request.

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