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Effect of ridge-furrow with plastic mulching and organic amendment on fertilizer-N fate in maize-soil system: A ^{15}N isotope tracer study

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The implementation of ridge-furrow with plastic film mulching has the potential to enhance crop yields and water productivity, particularly in black soil regions. However, the synergistic impacts of combining ridge-furrow with plastic mulching alongside with various organic amendments on maize yield and nitrogen fertilizer utilization efficiency remain unclear. Using ^{15}N-labeled tracing technology, we investigated fertilizer-N recovery of maize, distribution, fertilizer-N residual in soil, and nitrogen fertilizer loss across six treatments: non-mulched flat with non-organic amendment (FN), non-mulched flat with straw amendment (FS), non-mulched flat with biochar amendment (FBC), ridge-furrow with plastic mulching without organic amendment (RN), ridge-furrow with plastic mulching with straw amendment (RS), and ridge-furrow with plastic mulching with biochar amendment (RBC). The results revealed that ridge-furrow with plastic mulching in comparison to non-mulched flat, led to a significant increase in maize dry biomass accumulation, yield, and the rate of fertilizer-N recovery in maize (NRE) by 8.57%–12.36%, 10.08%–15.13%, and 2.22%–3.18%, respectively. The rate of fertilizer-N residual in soil (NSR) and fertilizer-N loss (NLS) decreased by 0.5%–2.04% and 0.78%–3.21%, respectively. In addition, the straw and biochar amendments under different planting methods promoted NRE in plants and NSR in soil, reducing NLS. Compared with non-organic amendment treatments, the inclusion of straw and biochar amendments resulted in increased NRE and NRS by 1.64%–6.20% and 0.12%–2.18%, while NLS decreased by 1.76%–7.78%. Biochar amendment treatment exhibited significantly higher nitrogen accumulation and NRE compared to the straw amendment treatment. Overall, ridge-furrow with plastic mulching combined with biochar amendment proved to be an effective method to enhance nitrogen fertilizer utilization of maize in the black soil regions, improving both yield and nitrogen fertilizer utilization efficiency.

KEYWORDS

ridge-furrow film mulching, maize, organic amendment, black soil, fertilizer-N fate

1 Introduction

With the persistent global population growth, the persistent demand for food is exerting unprecedented pressure on agricultural production systems, which is exacerbated by the dwindling availability of arable land resources (Quan et al., 2020; Jiang et al., 2023). To meet this growing demand, nitrogen fertilizer is being used extensively in agricultural production, particularly to increase crop yields and ensure food security. However, the perceived advantages of nitrogen fertilizer in terms of increased productivity have frequently been overestimated, leading to its overuse and reduced efficiency, and even leading to serious nitrogen pollution problems in certain regions (Zhang et al., 2020; Du et al., 2022). Previous studies indicated that only about 20%–30% of fertilizer-N was utilized by crops after entering the soil-crop system, with the remaining portion either residing in the clay layer or escaping into the environment, resulting in serious environmental pollution (Zheng et al., 2018). Therefore, accurately quantifying the fate of fertilizer-N in the soil-crop system, particularly its absorption by crops and subsequent loss, is crucial for improving nitrogen fertilizer efficiency, crop productivity, and ensuring national food security (Zheng et al., 2019; Wang et al., 2020).

The Northeast Black Soil Region is an important agricultural production center in China. In recent years, the adoption of ridge-furrow with plastic mulching planting has been widely adopted to address crop drought and increase yields. Compared to traditional non-mulched flat planting, ridge-furrow with plastic mulching planting helps accumulate water, elevate topsoil temperature and humidity, providing an optimal water and thermal environment for plant growth (Li W. et al., 2023; Li Z. et al., 2023). Numerous studies have indicated that thin film coverage significantly enhanced microbial biomass and soil fertility, reduced evaporation and promoted crop biomass accumulation and yield improvement (Li et al., 2022). However, research on nitrogen utilization by crops under ridge-furrow with plastic mulching planting in the Northeast Black Soil Region was not sufficiently deep, leaving the situation regarding nitrogen recovery, residue, and loss for maize fertilizer-N unclear. In particular, local farmers had applied excessive nitrogen fertilizer for a prolonged period, leading to reduced nitrogen fertilizer utilization efficiency and crop productivity, resulting in a range of environmental problems (Fang et al., 2022; Liu et al., 2022). To achieve efficient and sustainable agricultural development in the Northeast Black Soil Region, it is crucial to identify field management practices compatible with ridge-furrow plastic mulching, enhance crop nitrogen use efficiency and productivity, and promote agricultural sustainability.

Returning crop straw and biochar to the field significantly improves soil fertility and the comprehensive utilization efficiency of crop resources, making them effective strategies for increasing crop yields and enhancing crop nitrogen fertilizer utilization efficiency (Ding et al., 2022; Hao et al., 2022). Research indicated that using straw as an external organic input into the soil could significantly reduce soil bulk density, increase soil porosity, improve soil aeration and permeability, facilitate the transformation and transfer of soil nutrients, and enhance plant absorption and utilization of nitrogen fertilizer (Xu et al., 2021; Chen et al., 2022). Biochar, a stable product derived from biomass through the process of high-temperature anaerobic carbonization and recognized as an innovative and environmentally benign material, could increase soil active organic carbon content, soil microbial quantity, and metabolic activity (Craswell et al., 2021). Similarly, biochar could enhance soil organic carbon content, microbial activity, and nutrient availability, contributing to improved soil fertility and crop nitrogen recovery (Liao et al., 2021; Zhang J. et al., 2022). Although studies suggested that the application of straw and biochar could promote crop nitrogen utilization to a certain extent, their effects differ and may produce different results under different agricultural management practices. Currently, understanding the fate of nitrogen fertilizer under ridge-furrow with plastic mulching planting with straw or biochar amendment in maize is limited.

In summary, to better understand the fate of nitrogen fertilizer in maize under ridge-furrow with plastic mulching planting combined with straw and biochar amendment in the Northeast Black Soil Region, this experiment employed the method of setting up ^{15}N tracer micro-zones in the field to investigated the effects of straw or biochar amendment under non-mulched flat planting and ridge-furrow with plastic mulching planting on fertilizer-N recovery in maize and fertilizer-N residual in soil. We analyzed the uptake and distribution patterns of fertilizer-N in various organs of maize under different treatments, aiming to elucidate the fate of fertilizer-N in the soil-crop system and explore the application potential of straw or biochar in enhancing nitrogen efficiency in maize under ridge-furrow with plastic mulching planting. In conclusion, this research represented a significant exploration to uncover the fate of nitrogen fertilizer in maize, providing valuable insights into rainfed land production potential in the Northeast Black Soil Region. These findings could provide robust support for reducing fertilizer usage, stabilizing grain supply, and achieving sustainable agriculture within the framework of green development.

Therefore, we hypothesized that organic amendments affected crop yield and the absorption and utilization of fertilizer by maize. Both ridge-furrow with plastic mulching and the application of organic amendments influence the accumulation and utilization of nitrogen fertilizer and its distribution within the soil-crop system. In this study, we observed the maize yield and nitrogen accumulation under ridge-furrow with plastic mulching and non-mulched flat planting conditions combined with straw or biochar amendments through field experiments combined with ^{15}N tracer micro-zones, and determined the distribution of fertilizer nitrogen in various maize organs and the soil. The objectives of this study were as follows: 1) investigate the fate of fertilizer nitrogen in the maize cropping system in response to organic fertilizer application and ridge-furrow with plastic mulching; and 2) explore the potential application of straw or biochar combined with ridge-furrow with plastic mulching in improving nitrogen use efficiency in maize.

2 Materials and methods

2.1 Description of the study site

The experiments were conducted in Xinyi village, Harbin City, Heilongjiang Province (126°44′E, 45°44′N) from May to October in 2021. A temperate continental monsoon climate characterizes the research region, with a long–term mean annual surface evaporation of 1,508 mm, an average annual precipitation of 423 mm, a frost-free

TABLE 1 Soil physical and chemical properties.

Soil depth (cm)	Particle size distribution			Total organic carbon content	Total nitrogen content	Total phosphorus content	Total potassium content
	Sand	Silt	Clay	(g·kg^{-1})	(g·kg^{-1})	(g·kg^{-1})	(g·kg^{-1})
0–20	56.3	30.6	13.1	25.42	1.01	0.79	22.26
20–40	54.2	31.9	13.9	23.41	0.64	0.74	22.07
40–60	52.7	32.4	14.9	13.18	0.33	0.67	21.84

period of 141 days, an annual average temperature of 5.6°C and an annual sunshine hours of 2,600 h. The soil type for testing is black soil, the basic physical and chemical properties of the soil were listed in Table 1.

2.2 Straw and biochar

The total carbon content of the test maize straw was 384.6 g·kg^{-1}, total nitrogen 10.19 g·kg^{-1}, total phosphorus 0.49 g·kg^{-1}, and total potassium content 6.57 g·kg^{-1}. The test straw was prepared in 2020 by a plot experiment with the same variety of maize, and the test biochar was produced by Shandong Industrial Biomass Engineering Technology Research Center and produced under anaerobic conditions of maize stover at 400°C–500°C with an average conversion rate of 33%. The total carbon, nitrogen and potassium of biochar was 479.9 g·kg^{-1}, 8.13 g·kg^{-1} and 8.13 g·kg^{-1} potassium with a pH of 9.72.

2.3 Experimental design

The field experiment was conducted following a randomized complete block design with two-factor randomized block experiment. Factor 1 consisted of two different planting methods: non-mulched flat planting, ridge-furrow with plastic mulching planting; factor 2 involved three organic amendments: no amendment, adding 6.75 t/hm^2 of straw, and adding 2.25 t/hm^2 of biochar (the same amount of carbon as the straw amendment treatment).Thus, six treatments were included: non-mulched flat planting with non-organic amendment (FN), non-mulched flat planting with straw amendment (FS), non-mulched flat planting with biochar amendment (FBC), ridge-furrow with plastic mulching planting without organic amendment (RN), ridge-furrow with plastic mulching planting with straw amendment (RS), and ridge-furrow with plastic mulching planting with biochar amendment (RBC). Each treatment was replicated three times, with the plot area of 3 m × 8 m and the spacing between plots set at 1 m. In the ridge-furrow with plastic mulching planting treatment, the ridges were constructed with a height and width of 20 cm and 70 cm, respectively, while the furrow were dug to a depth and width of 20 cm and 30 cm, respectively. Each ridge was sown with two rows of seeds spaced 40 cm apart, with individual plants spaced 30 cm apart. Subsequently, the seeds were then covered with 0.04 mm thick plastic film. Following the previous season's corn harvest, corn straw (crushed to around 2–3 cm) or biochar were evenly scattered to the field's soil surface. Subsequently, they were homogeneously incorporated into the soil to a depth of 0–15 cm using a rotary tiller before being covered with film.

The corn plant was sown on 1 May 2021, at a planting density of 57500 plants ha^{-1} and harvested on 5 October 2021. Irrigation was exclusively conducted during the seedling stage, with no irrigation applied during the growth stage. The total irrigation amount during the seedling phase was 270 mm. The treatments were fertilized with phosphorus fertilizer (calcium superphosphate, 46% P_2O_5) at a rate of 90 kg/hm^2, potassium fertilizer (potassium sulfate, 54% K_2O) at a rate of 120 kg/hm^2 and nitrogen fertilizer (urea, 46% N) at a rate of 240 kg/hm^2. Phosphate and potash fertilizer were applied once as base fertilizer, while half of the nitrogen fertilizer was applied at the base stage, with the remaining half administered subsequently at the nodulation stage.

To monitor the fate of the ^{15}N-labelled fertilizer, a micro-zone test was carried out by pre-installing a bottomless rectangular PVC frame a length of 2 m, a width of 1.46 m and a height of 0.6 m in the middle of each experimental plot prior to the application of the base fertilizer urea, and exposing it to the surface of the ground by 15 cm in order to prevent the exchange of nitrogen and water in and out of the micro-zone. The nitrogen fertilizer used in the micro-zone was 10.22% abundance of ^{15}N-labelled urea (Shanghai Research Institute of Chemical Industry), all the ^{15}N-labelled urea was dissolved in 2 L of distilled water, and sprayed uniformly on the soil surface of the micro-zone using a hand sprayer, and the application rate was consistent with that of the experimental plots matches.

2.4 Biomass and soil sampling and measurements

Soil and plant samples are collected during the maize harvesting period. Soil samples were collected from six randomly points in the experimental plots and micro-plots at depths of 0–20 cm, 20–40 cm, and 40–60 cm. The soil samples were air-dried at room temperature, and visible fresh roots and organic debris were removed with forceps. From each plot, three rows of representative maize plants, and from each row, 10 maize plants were randomly harvested to measure the 100-grain weight (at 14% water content) and yield. Subsequently, the maize plants were meticulously cleaned and divided into three parts: stems, leaves and grains. These parts were then oven-dried at 70°C until reaching a constant mass, after which they were weighed.

Subsequently, five ^{15}N-labelled maize plants were randomly selected in each micro-area and placed in an oven at 105°C for 30 min, dried at 70°C until a constant weight was reached and crushed in a ball mill and sieved through a 100-mesh sieve, mixed. The total N concentration and ^{15}N atom% of plant and soil samples

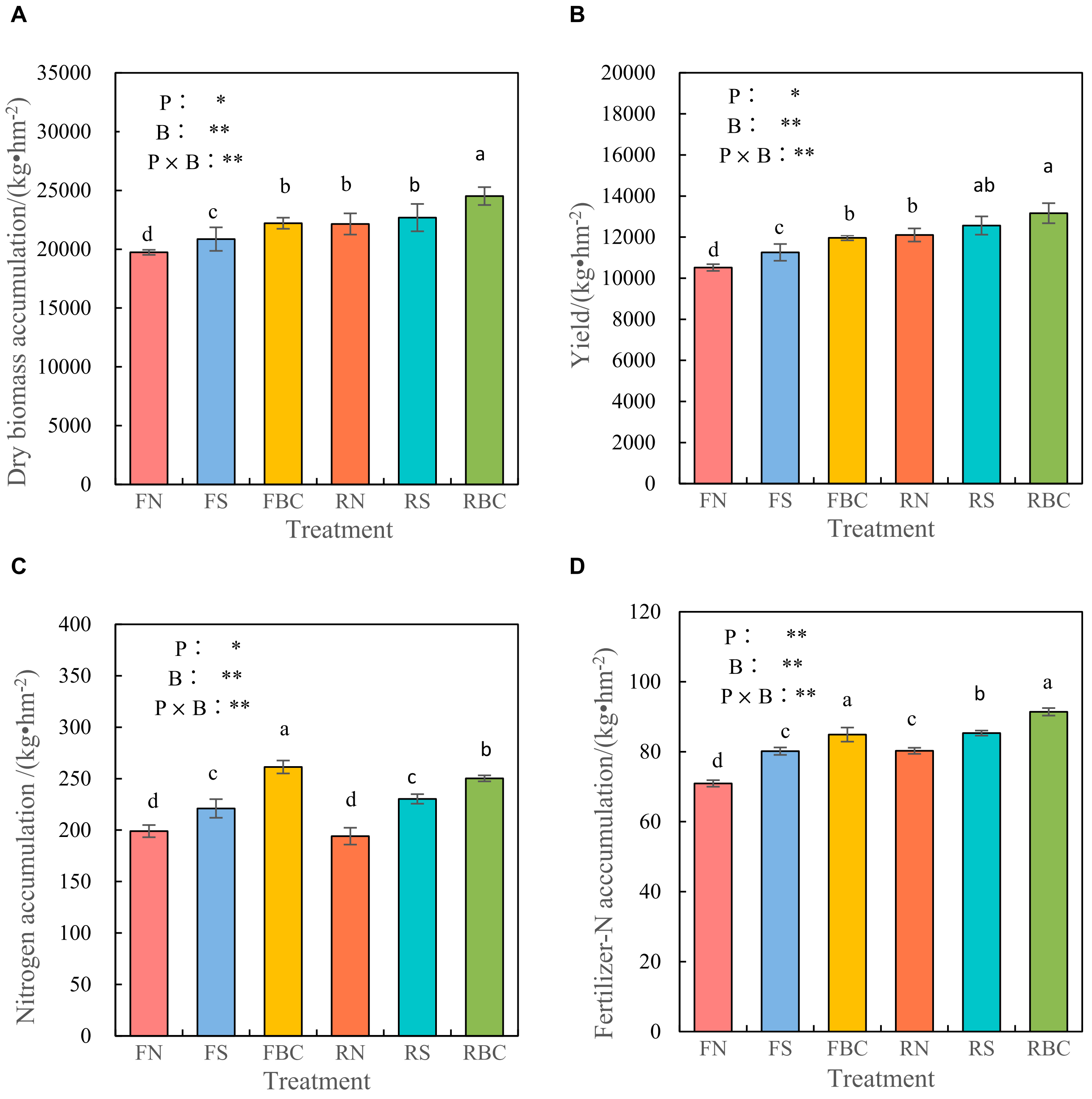

FIGURE 1
Dry biomass **(A)**, yield **(B)**, nitrogen accumulation **(C)** and fertilizer-N accumulation in maize **(D)** under different treatments. Different letters in the same column indicate significant differences ($p < 0.05$) among different treatments; P indicates planting methods, B indicates organic amendment. The numbers in the analysis of variance are *F* values. ns: $p > 0.05$; *: $p < 0.05$; **: $p < 0.01$. Error bars represent standard errors around means ($n = 3$). FN: non-mulched flat planting with non-organic amendment; FS: non-mulched flat planting with straw amendment; FBC: non-mulched flat planting with biochar amendment; RN: ridge-furrow with plastic mulching planting without organic amendment; RS: ridge-furrow with plastic mulching planting with straw amendment; RBC: ridge-furrow with plastic mulching planting with biochar amendment.

are determined using a Flash 2000 HT elemental analyzer (Thermo Fisher Scientific) interfaced to an isotope mass spectrometer (DeLTA V Advantage, Thermo Fisher Scientific) (EA-IRMS).

The fertilizer-N recovery efficiency (NRE, %) of plants in the micro-plots at maturity was calculated by the method of Zheng et al. (2018); Wang et al. (2020). Values for plant or soil N derived from fertilizer (N_{dff}) and soil (N_{dfs}) and fertilizer N recovery efficiency (*NRE*) were estimated based on the following equations:

$$N_{dff} = \frac{N_P - N_A}{N_F - N_A} \times 100\% \tag{1}$$

$$N_{dfs} = 1 - N_{dff} \tag{2}$$

$$NRE = \frac{D_M \times N_C \times N_{dff}}{N_{Applied}} \times 100\% \tag{3}$$

$$NSR = \frac{D_M \times N_C \times N_{dfs}}{N_{Applied}} \times 100\% \tag{4}$$

$$NLS = 100 - NRE - NSR \tag{5}$$

where N_{dff} and N_{dfs} are the plant N derived from fertilizer and soil, %; N_P is the atom% ^{15}N abundance of crop sample, %; N_F is the atom% ^{15}N abundance of labeled fertilizer, %; N_A is atom % ^{15}N abundance in control whole-plant crop, %, with a background abundance of 0.3663%; NRE is the rate of fertilizer-N in plant uptake, %; D_M is dry biomass accumulation of maize plant, kg/hm^2; N_C was the nitrogen content of maize plants, %; NSR is the rate of fertilizer-N residual in soil, %; NLS is the rate of the fertilizer-N loss, %.

2.5 Statistical analysis

The interaction effects of planting methods and organic amendment on maize dry biomass accumulation, yield, nitrogen accumulation and the fate of ^{15}N-labeled N were analyzed by a two-way analysis of variance (ANOVA). The threshold value for significance was set at $p < 0.05$. All statistical analyses were performed using SPSS 20.0 (SPSS Inc., Chicago, IL, United States). All the graphs were plotted by Origin 9.0 software (Origin Lab Corporation, MA, United States).

3 Results

3.1 Maize yield, dry biomass and nitrogen accumulation

Two-way ANOVA revealed that maize dry biomass, yield, nitrogen accumulation and fertilizer-N accumulation depended on planting methods, organic amendment and their interaction ($p < 0.05$) (Figure 1). Ridge-furrow with plastic mulching planting leaded to a substantial increase in maize dry biomass accumulation and yield compared with non-mulched flat planting ($p < 0.05$). Compared with non-mulched flat planting, the dry biomass accumulation and yield increased by 10.02%–15.08% and 8.76%–12.33% ($p < 0.05$), respectively, under the ridge-furrow with plastic mulching planting increased. Furthermore, compared with non-organic amendment treatment, the maize yield was increased by 7.02%–13.76% ($p < 0.05$), dry biomass accumulation was increased by 5.71%–12.55% ($p < 0.05$), nitrogen accumulation increased 11.07%–33.02% ($p < 0.05$) and fertilizer-N accumulation increased 6.98%–18.54% ($p < 0.05$) under the straw and biochar amendment treatments. Notably, the biochar amendment was more effective than straw amendment in increasing crop yield and dry biomass accumulation. The incorporation of organic amendment under ridge-furrow with plastic mulching planting resulted in superior outcomes, with the highest maize yield, dry biomass accumulation, and fertilizer-N accumulation observed under the RBC treatment.

3.2 Fertilizer-N distribution in maize plants

Planting methods, organic amendment and their interaction significantly affected the fertilizer-N accumulation and ratio in total fertilizer-N accumulation in different organs of maize (Figure 2). Compared with non-mulched flat planting, ridge-furrow with plastic mulching planting increased the fertilizer-N accumulation in different maize organs by 4.81%–12.54%. Both straw and biochar amendment treatments promoted fertilizer-N accumulation by maize organs, with biochar amendment exhibiting a more pronounced enhancing effect. Across all treatments, fertilizer-N distribution in maize organs followed a descending order of grains, leaves, and stems ($p < 0.05$). Specifically, compared to non-organic amendment treatment, the straw amendment treatment increased fertilizer-N accumulation in maize stems, leaves, and grains by 6.78%–14.83%, 3.61%–12.24%, and 5.00%–12.10%, respectively; And under the biochar amendment treatment, the fertilizer-N accumulation in maize stems, leaves, and grains increased by 10.28%–14.83%, 13.04%–14.35%, and 12.69%–19.92%, respectively ($p < 0.05$). Meanwhile, the ratio in total fertilizer-N accumulation in maize grains increased by 1.79%–3.70% ($p < 0.05$), compared with stems and leaves, under the straw and biochar amendment treatment. In all treatments, the RBC treatment showed the highest fertilizer-N accumulation of maize organs, and maize grains also demonstrated the largest increment in fertilizer-N accumulation, and the ratio in total fertilizer-N accumulation in RBC treatment showed the higher in maize organs.

3.3 Fertilizer-N residual and distribution in soil

The fertilizer-N residual in soil across depths of 0–60 cm showed significant responses to planting methods, organic amendment and their interactive effects (Table 2). The distribution pattern of fertilizer-N residual amounts and ratio in total fertilizer-N residual in soil were similar among different treatments, showing a significant decrease with increasing soil depth ($p < 0.05$). Under the RN treatment, the fertilizer-N residual amount in the 0–20 cm and 20–40 cm soil layers decreased by 9.76% and 6.67%, compared to the FN treatment, and increased 6.20% in the 40–60 cm soil layer ($p < 0.05$). Under different planting methods, both straw and biochar amendment treatments demonstrated the capability to retain fertilizer-N in the 0–20 cm soil, reducing the downward movement of fertilizer-N. Compared to non-organic amendment treatments, the straw amendment treatment, resulted in an increase in the fertilizer-N residual amount and ratio in total fertilizer-N residuals in the 0–20 cm soil by 14.55%–20.69% and 8.05%–9.69% ($p < 0.05$), respectively; Similarly, under biochar amendment treatment, the fertilizer-N residual amount and ratio in total fertilizer-N residuals in the 0–20 cm soil increased by 31.27%–32.83% and 10.58%–11.93% ($p < 0.05$), respectively.

3.4 The fates of fertilizer-N in maize cropping system

Planting methods, organic amendment and their interaction significantly affected the fertilizer-N recovery in maize, fertilizer-N residual in soil, and fertilizer-N loss (Table 3). In each treatment, the rate of fertilizer-N recovery (NRE) in maize ranged from 29.56% to 38.09%, the rate of fertilizer-N residual in soil (NSR) ranged from

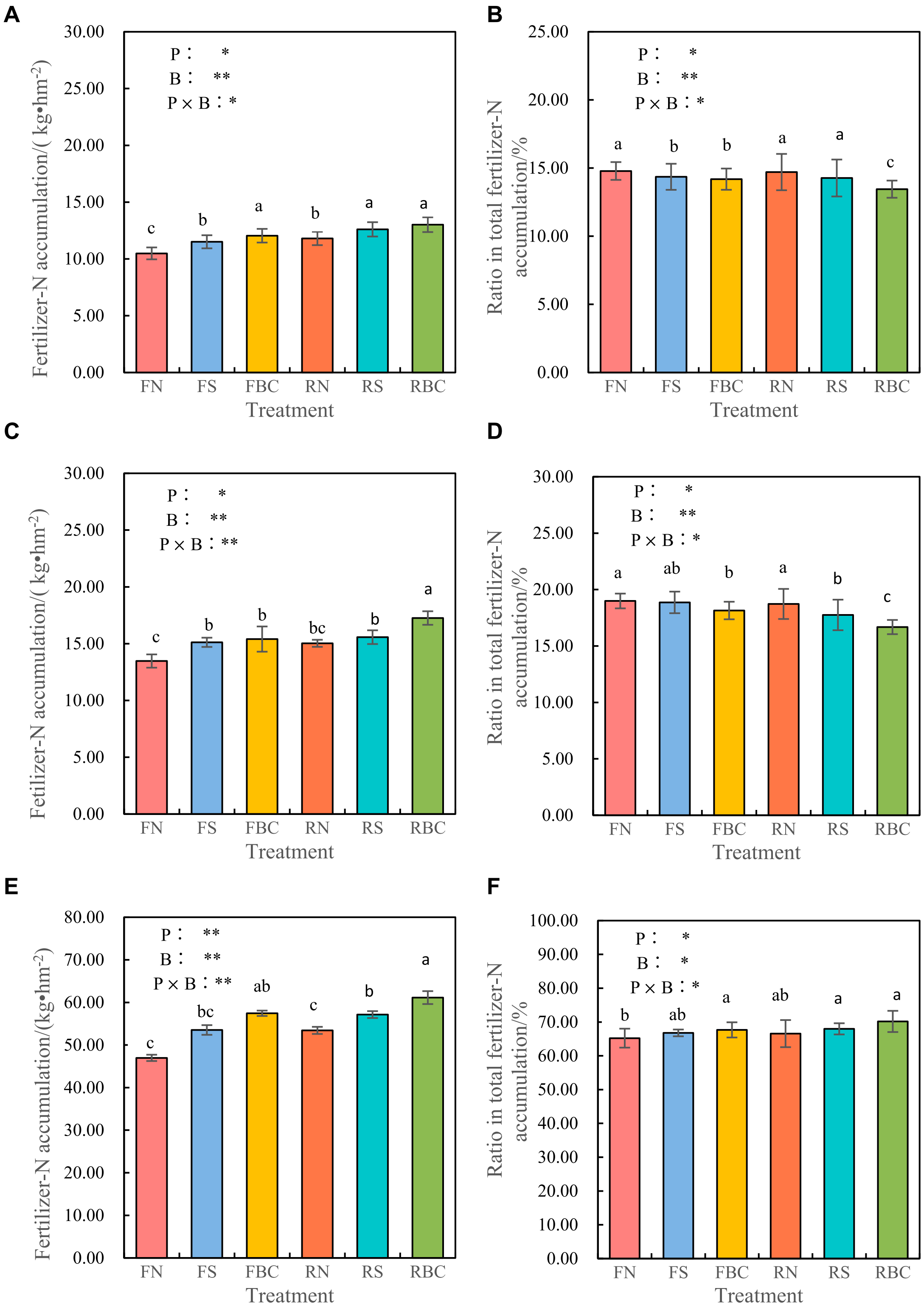

FIGURE 2
Fertilizer N in each organ in maize under different treatments. Different letters in the same column indicate significant differences ($p < 0.05$) among different treatments; P indicates planting methods, B indicates organic amendment; The numbers in the analysis of variance are F values. ns: $p > 0.05$; *: $p < 0.05$; **: $p < 0.01$. Error bars represent standard errors around means ($n = 3$). FN: non-mulched flat planting with non-organic amendment; FS: non-mulched flat planting with straw amendment; FBC: non-mulched flat planting with biochar amendment; RN: ridge-furrow with plastic mulching planting without organic amendment; RS: ridge-furrow with plastic mulching planting with straw amendment; RBC: ridge-furrow with plastic mulching planting with biochar amendment.

TABLE 2 The fertilizer-N residual in 0–60 cm soil under different treatments.

Treatment	0–20 cm		20–40 cm		40–60 cm	
	Fertilizer-N residual/ (kg•hm^{-1})	Ratio in total fertilizer-N residual/%	Fertilizer-N residual/ (kg•hm^{-1})	Ratio in total fertilizer-N residual/%	Fertilizer-N residual/ (kg•hm^{-1})	Ratio in total fertilizer-N residual/%
FN	30.91 ± 1.24c	50.65 ± 2.72c	18.01 ± 0.71a	29.50 ± 1.55a	12.11 ± 0.6ab	19.85 ± 1.32b
FS	35.4 ± 1.41b	60.34 ± 3.21a	16.84 ± 1.21d	27.44 ± 2.75b	9.09 ± 0.75c	14.23 ± 1.69d
FBC	40.57 ± 2.68a	61.23 ± 5.4a	17.48 ± 0.65b	26.38 ± 1.32b	8.21 ± 0.96bc	12.22 ± 1.93de
RN	27.89 ± 1.15d	48.46 ± 2.67d	16.8 ± 0.89c	29.20 ± 2.08a	12.87 ± 0.41a	22.35 ± 0.95a
RS	33.67 ± 0.96c	56.22 ± 2.24b	16.03 ± 0.45d	26.76 ± 1.04c	10.19 ± 1.2b	17.02 ± 2.8c
RBC	37.05 ± 1.43b	60.39 ± 3.11a	17.56 ± 1.21b	28.62 ± 2.63a	6.75 ± 0.76d	10.99 ± 1.67e
Two-way ANOVA						
P	**	**	*	*	*	*
B	**	**	ns	ns	**	**
P×B	**	**	*	*	*	*

Note: Different lower letters in the same column indicate significant differences ($p < 0.05$) among different treatments, different upper letters in the same line indicate significant differences ($p < 0.05$) among different soil layer; P indicates planting methods, B indicates organic amendment; The numbers in the analysis of variance are F values. ns: $p > 0.05$; *: $p < 0.05$; **: $p < 0.01$. Error bars represent standard errors around means ($n = 3$). FN: non-mulched flat planting with non-organic amendment; FS: non-mulched flat planting with straw amendment; FBC: non-mulched flat planting with biochar amendment; RN: ridge-furrow with plastic mulching planting without organic amendment; RS: ridge-furrow with plastic mulching planting with straw amendment; RBC: ridge-furrow with plastic mulching planting with biochar amendment.

TABLE 3 The fate of^{15}N urea including fertilizer-N recovery, fertilizer-N residual, and fertilizer-N loss in maize cropping system under different treatments.

Treatment	Fertilizer-N recovery		Fertilizer-N residual		Fertilizer-N loss	
	The amount of fertilizer-N recovery in maize	NRE/%	The amount of fertilizer-N residual in soil	NSR/%	The amount of fertilizer-N loss	NLS/%
	/(kg•hm^{-1})		/(kg•hm^{-1})		/(kg•hm^{-1})	
FN	70.94 ± 0.65d	29.56 ± 0.27d	61.02 ± 2b	25.43 ± 0.83b	108.04 ± 2.19a	45.02 ± 0.91a
FS	80.16 ± 1.59c	33.4 ± 0.66c	61.33 ± 1.61bc	25.55 ± 0.67bc	98.51 ± 2.85ab	41.05 ± 1.19ab
FBC	84.9 ± 0.31b	35.38 ± 0.13b	66.26 ± 2.29a	27.61 ± 0.95a	88.84 ± 2.45c	37.02 ± 1.02c
RN	80.27 ± 1.19c	33.45 ± 0.5c	57.56 ± 0.17c	23.98 ± 0.07c	102.18 ± 1.36a	42.58 ± 0.57a
RS	85.32 ± 1.76b	35.55 ± 0.73b	59.89 ± 2.55c	24.95 ± 1.06c	94.79 ± 1.84b	39.50 ± 0.77b
RBC	91.41 ± 0.69a	38.09 ± 0.29a	61.36 ± 2.91b	25.57 ± 1.21b	87.23 ± 2.28c	36.35 ± 0.95c
Two-way ANOVA						
P	*	*	*	*	*	*
B	**	**	**	**	**	**
P×B	**	**	*	*	**	**

Note: Different letters in the same column indicate significant differences ($p < 0.05$) among different treatments; P indicates planting methods, B indicates organic amendment; NRE, was the rate of fertilizer-N recovery in plant; NSR, was the rate of fertilizer-N residual; NLS, was the rate of fertilizer-N loss. The numbers in the analysis of variance are F values. ns: $p > 0.05$; *: $p < 0.05$; **: $p < 0.01$. Error bars represent standard errors around means (n = 3). FN: non-mulched flat planting with non-organic amendment; FS: non-mulched flat planting with straw amendment; FBC: non-mulched flat planting with biochar amendment; RN: ridge-furrow with plastic mulching planting without organic amendment; RS: ridge-furrow with plastic mulching planting with straw amendment; RBC: ridge-furrow with plastic mulching planting with biochar amendment.

23.84% to 27.61%, and the rate of fertilizer-N loss (NLS) ranged from 36.53% to 45.02% ($p < 0.05$). Compared with non-mulched flat planting, ridge-furrow with plastic mulching planting effectively increased fertilizer-N recovery in maize and reduced fertilizer-N loss ($p < 0.05$). Under different planting methods, both straw and biochar amendment treatments promoted NRE and reduced NLS in maize ($p < 0.05$). Compared with non-organic amendment, under straw amendment treatment, the NRE increases 2.10%–3.84%, the NSR increases 0.12%–0.97%, and NLS decreases 3.08%–3.97%. Similarly, under biochar amendment treatment, NRE increased by 4.64%–5.82%, NSR increased by 1.58%–2.18%, and the NLS decreased by 6.22%–8.00% ($p < 0.05$). The benefit of increasing fertilizer-N recovery in plant and reducing fertilizer-N loss were more pronounced in the biochar treatment than only straw amendment treatment. Notably, the RBC treatment exhibited the highest NRE and the lowest NLS among all treatments.

4 Discussion

4.1 Dry matter accumulation and yield in maize

Ridge-furrow with plastic mulching planting, a prevalent method in the Northeast Black Soil Region, has garnered attention for its ability to enhance crop water supply, promote root growth, and optimize soil resource availability (Zhang F. et al., 2022; Wang et al., 2022). This technique improves soil water and thermal conditions, thereby fostering crop growth and augmenting yields. In this study, ridge-furrow with plastic mulching planting demonstrated significant advantages over non-mulched flat planting, with maize dry biomass and yield increasing by 15.08% and 12.33%, respectively (Figure 1). Furthermore, the incorporation of straw and biochar amendment treatments exerted notable effects on maize yield and dry biomass accumulation. Compared to the FN treatment, the FS treatment led to a 7.02% increase in dry biomass accumulation and a 5.71% increase in yield, while the FBC treatment resulted in a 13.76% increase in dry biomass accumulation and a 12.55% increase in yield (Figure 1). These results indicated that the straw and biochar amendments as essential measures for agricultural resource recycling can help to improve soil structure and increase soil porosity, thereby improving soil aeration and water retention capacity and providing a better growing environment for crop roots, thus increasing crop yields.

Some studies have indicated that the main reasons for contributing to yield enhancement are the retention of nutrients such as nitrogen and phosphorus in the soil. Additionally, treatments involving straw and biochar amendment have been shown to address soil nutrient deficiencies, thereby promoting maize nutrient absorption and yield enhancement (Xia et al., 2020; Hu et al., 2021). Compared with the straw amendment treatment, the biochar amendment treatment, characterized by its highly aromatic and insoluble nature, extensive surface area and complex pore structure, has been observed to effectively reduce soil bulk density and compaction, lowered mechanical resistance to roots and significantly enhanced soil water and nutrient conditions, favoring increased crop yield (He et al., 2023). Biochar amendment has the property of releasing nutrients slowly, which can continue to provide nutrients such as nitrogen, phosphorus and potassium required for plant growth over a period of time, whereas after straw amendment is returned to the field, the rate of nutrient release may be faster, leading to fluctuations in nutrient concentrations in the soil in the short term (Hu et al., 2021; Zhao et al., 2023). Due to its combined effects of soil improvement, nutrient management, microbial activity enhancement, nutrient loss reduction, carbon sequestration and emission reduction, the biochar amendment treatment showed a superior to straw amendment treatment in terms of yield enhancement.

Moreover, the impact of organic amendment on maize nitrogen accumulation and yield under ridge-furrow with plastic mulching planting was significantly higher than only organic amendment ($p < 0.05$). This may be attributed to the ability of straw and biochar amendment treatments to ameliorate soil compaction issues caused by ridge-furrow with plastic mulching planting, optimizing the crop growth environment, reducing nutrient loss, and significantly affecting fertilizer nutrient utilization and crop yield increasing.

4.2 Fertilizer-N accumulation and distribution in maize plants

Nitrogen is a crucial factor affecting farmland productivity and sustainability. The main pathways for crops to obtain nitrogen are through the application of chemical nitrogen fertilizer and the utilization of organic and inorganic nitrogen in the soil. Effective nitrogen accumulation and distribution are crucial for enhancing crop yields (Li X. et al., 2023). This experiment demonstrated that nitrogen accumulation in maize under straw and biochar amendment treatments promoted fertilizer-N accumulation in maize, with the biochar amendment treatment exhibiting even higher levels of fertilizer-N accumulation compared to the straw amendment treatment. This disparity could potentially be attributed to the capacity of straw and biochar amendments to provide carbon sources to the soil.

When soil contains sufficient carbon sources, 20%–55% of fertilizer-N could transform into organic or clay forms under microbial action, effectively fixing it within the soil (Zhang M. et al., 2022; Du et al., 2022). And compared to straw, biochar had a larger surface area and a more complex pore structure, enhancing adsorption performance, resulting in greater retention of fertilizer-N in the soil, as corroborated by this study (Table 3), this phenomenon promotes crop fertilizer-N accumulation. Compared to non-mulched flat planting, ridge-furrow with plastic mulching planting increased fertilizer-N accumulation across various maize organs. This could be attributed to the maintenance of optimal water retention conditions by ridge-furrow with plastic mulching planting, which not only increased surface soil moisture content but also enhanced surface soil temperature, thereby promoting the absorption and utilization of fertilizer-N by crops (Zhao et al., 2023). Additionally, our research found that under different planting methods and organic amendment, the fertilizer-N accumulation in maize grains was significantly higher than in other organs. The fertilizer-N accumulation in maize grains accounted for 65.59%–68.12% of the total fertilizer-N accumulation in the plant. The stems and leaves account for 14.1%–15.21% and 17.68%–19.21% (Table 3), respectively, which was consistent with previous studies (Zhang et al., 2018; Xia et al., 2022). Furthermore, compared with non-mulched flat planting, ridge-furrow with plastic mulching planting combined with straw and biochar amendments increased the fertilizer-N accumulation by various maize organs. The fertilizer-N accumulation of maize stems, leaves and grains increased by 10.28%–24.11%, 14.81%–28.12%, and 14.42%–30.31%, respectively (Figure 2). Moreover, under ridge-furrow with plastic mulching planting combined with biochar amendment, the fertilizer-N accumulation increment in maize grain was the highest, increasing by 24.97% and 7.11% compared with stems and leaves, respectively. This indicated that optimizing planting methods and organic amendment could adjust the absorption and utilization of fertilizer-N by various organs, more efficiently enhancing fertilizer-N accumulation by maize grains, promoting the transfer of nutrients to reproductive organs and facilitating the increase in maize yield.

4.3 The fates of fertilizer-N in soil-crop system

The fates of fertilizer-N applied to the soil primarily includes crop absorption and utilization, residual presence in various forms in the soil, and losses through different mechanisms and pathways in the soil-crop system (Ullah et al., 2021; Anning et al., 2023). In this study, the NRE ranged from 29.56% to 38.09%, the NSR ranged from 23.84% to 27.61%, and the NLS ranged from 36.53% to 45.02% (Table 3). Planting methods, organic amendment and their interaction significantly affected the fertilizer-N fates in maize. Ridge-furrow with plastic mulching planting, along with straw and biochar amendments, increased crop fertilizer-N recovery and fertilizer-N residual in soil, thereby reducing fertilizer-N loss. The NRE in maize was highest under RBC treatment, increasing by 8.42% compared to FN treatment, which could be attributed to the stabilizing effect of ridge-furrow with plastic mulching planting and biochar amendment on soil structure. The combined effect of ridge-furrow with plastic mulching planting and biochar amendment could be interpreted as an increase in soil temperature and moisture content, enhancing the activity of soil microorganisms and promoting nitrogen absorption and utilization.

The fertilizer-N residual in soil was a crucial source for increasing soil nitrogen storage and subsequent plant uptake (Ren et al., 2024). Experimental resulted showed that different planting methods and organic amendment significantly affected the fertilizer-N residue in soil at depths of 0–60 cm. Under the biochar amendment treatment, fertilizer-N residual in soil increased by 6.60% compared to treatment without organic amendment, and fertilizer-N residual in the 0–20 cm soil layer increased by 10.58%, accounting for 48.46%–61.23% of the total residual (Table 2). This is due to the chemical adsorption of straw and biochar and the nitrogen-fixing action of related microorganisms, resulting in a large amount of fertilizer-N residual in the surface soil and reducing the movement of fertilizer-N to the lower soil layers. In addition, considering that the main root zone of most maize plants is in the 0–40 cm depth range (Zhang et al., 2020; Cao et al., 2022), under straw and biochar amendment treatments, more nutrients were present near the root zone, providing a favorable root environment for maize root growth and dry biomass accumulation. Therefore, the adoption of straw and biochar amendment treatments under ridge-furrow with plastic mulching planting could be an effective cultivation method for utilizing straw, enriching soil fertility, and increasing spring maize yield. Moreover, previous research has highlighted that a significant portion of nitrogen fertilizer lost occur due to the generation of greenhouse gases such as N_2O through nitrification or denitrification reactions (Li X. et al., 2023; Li Y. et al., 2023). Ridge-furrow with plastic mulching planting with biochar amendment reduced the amount of nitrogen fertilizer loss by 8.67%, compared to the FN treatment, thereby reducing the emission of greenhouse gases such as N_2O. Hence, the integration of biochar amendment combined with ridge-furrow with plastic mulching planting is crucial for crop production and ecological conservation. Compared with individual measures, this planting method has synergistic benefits for fertilizer-N utilization in spring maize, promoting plant growth, reducing fertilizer-N loss, and increasing yield. Therefore, in the Northeast Black Soil Region, ridge-furrow with plastic mulching combined with biochar amendment as a means to enhance nitrogen fertilizer efficiency can contribute to increased maize yield, effective resource utilization, and better fulfillment of current sustainable agriculture needs.

5 Conclusion

Compared with traditional non-mulching flat planting, ridge-furrow with plastic mulching planting has demonstrated its capacity to promote the accumulation of maize dry biomass accumulation and increase yields. This method improves nitrogen fertilizer absorption, resulting in notable benefits such as increased Nitrogen Recovery Efficiency (NRE) and decreased Nitrogen Losses (NLS). Both straw and biochar amendments contribute to enhanced maize dry biomass and nitrogen accumulation, consequently boosting yields. Notably, maize grains exhibit the highest nitrogen absorption rates, especially under straw and biochar amendments, leading to an increase in Nitrogen Soil Residual (NSR) primarily concentrated in the topsoil layer, thus effectively reducing NLS. The efficacy of biochar amendment surpasses that of straw, further improving NRE and yield of maize. Ridge-furrow with plastic mulching and biochar amendment combination produces the highest maize yield and NRE, underscoring its potential in enhancing fertilizer efficiency and crop productivity. By promoting the recovery and accumulation of fertilizer-N by various maize organs, reducing fertilizer-N loss, and simultaneously increasing yield, this method proves to be an effective strategy for advancing efficient nitrogen fertilizer utilization and resource recycling in agriculture.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

QM: Data curation, Investigation, Writing–original draft. JL: Methodology, Project administration, Resources, Writing–review and editing. ZC: Data curation, Formal analysis, Funding acquisition, Writing–review and editing.

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Conflict of interest

Publisher's note

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