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Organic fertilizer in combination with zeolite enhanced maize yield with lower greenhouse gas emissions in sandy loam soil in North China

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Introduction: There is limited knowledge about how co-applying organic fertilizer and zeolite influences maize yield and soil greenhouse gas (GHG) emissions in sandy loam soil.
Methods: In the present study, a 3-year maize field experiment was conducted on a sandy loam soil in the North China Plain with five treatments: no added fertilizer (control, CK), synthetic fertilizer (SF), organic fertilizer replacing 30% synthetic N fertilizer (OF), synthetic fertilizer with zeolite (ZSF), and organic fertilizer with zeolite (ZOF).
Results: Results showed that, compared with the SF treatment, the ZOF treatment significantly increased yield by 14.72–23.61% in each of the 3 years, ZSF by 13.91–15.59% in 2022 and 2023, and OF by 16.92% in 2023. Compared with ZSF, the cumulative CO_2 emission was significantly increased by 4.52% in OF in 2023. Compared with SF, the average N_2O emission flux and cumulative (over 2022 and 2023) N_2O emissions were significantly reduced by 6.74–8.23% and 6.10–8.79% by OF, 9.29–11.86% and 9.23–10.85% by ZSF, and 7.59–11.24% and 12.27–16.06% by ZOF, respectively. Compared with SF, the total global warming potential (GWP) was significantly lower by 4.78% in ZOF in 2023, the greenhouse gas intensity (GHGI) was significantly lower over the 3 years of trials by 6.45–15.31% and 14.16–21.06% in treatments ZSF and ZOF, respectively, and was significantly lower by 10.53–13.13% in OF in 2022 and 2023. Compared with SF, the levels of available potassium and phosphorus content, dissolved organic carbon content, soil β-glucosidase activity, and microbial biomass carbon and nitrogen concentration in the ZOF treatment were significantly higher by 7.34, 8.90, 19.48, 9.20, 8.42, and 11.29%, respectively; however, soil NH_4^+-N and NO_3^--N were significantly lower by 9.08 and 9.30%, respectively. The beneficial yield effects were due mainly to the enhanced synchronization of nutrient availability, soil moisture, and microbial biomass, while the mitigation of N_2O emission was mainly attributed to the decreasing soil NO_3^- and NH_4^+ concentrations in response to ZOF.
Conclusion: Applying both organic fertilizer and zeolite achieved increased maize yield and positive environmental benefits. This strategy could be adopted to improve maize production, mitigate greenhouse effects caused by N_2O emissions, and improve soil quality in sandy loam soils.

KEYWORDS

greenhouse gas emissions, maize yield, sandy loam soils, combined organic fertilizer and zeolite, soil quality

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1 Introduction

Greenhouse gas (GHG) emissions from agricultural ecosystems, especially carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are increasing globally as a result of anthropogenic activities (Shakoor et al., 2021), and this has become a serious environmental concern (Zhong et al., 2021). Agriculture is recognized as a significant contributor to GHG emissions, accounting for nearly 12% of global anthropogenic emissions (Linquist et al., 2012). Meanwhile, enhancing agricultural productivity is essential for feeding the burgeoning global population. With limited arable land resources, agricultural intensification serves as an effective strategy for ensuring food security for the world's population (Kamran et al., 2018; Sapkota et al., 2020); however, these agronomic practices are closely associated with substantial GHG emissions (Chataut et al., 2023). Consequently, understanding the impacts of soil emissions of GHGs and identifying optimal agronomic interventions in order to strike a balance between crop production and soil GHG emissions is crucial for advancing sustainable agricultural production.

The North China Plain is a major cereal production region, accounting for 28% of the China's total maize production. In this region, sandy loam soils (>45% sand content) is one of the predominant types of farmland soil. Owing to its low clay content, this soil type has an inherently limited ability to form aggregates which, in turn, restricts its water-holding capacity and soil carbon sequestration (Huang and Hartemink, 2020; Colunga et al., 2025). The limited nutrient composition of this soil, along with its low cation-exchange capacity, further exacerbate leaching losses of available nutrients and compromise soil fertility retention. Additionally, the restricted water availability and erratic precipitation patterns in North China limit primary productivity, leading to inherently low farmland productivity in these areas (Nielsen and Ball, 2015). In this region, fertilizer application plays a decisive role in enhancing maize production but is inextricably linked with stimulating soil GHG emissions (Tan et al., 2017; Cui et al., 2018; Huang et al., 2024; Wang et al., 2024). Decades of excessive fertilization and suboptimal management practices have collectively degraded soil quality (particularly in physicochemical and biological properties) and intensified GHG emissions across the region.

To restore soil quality, improve agricultural resilience and production, and mitigate GHG emissions, various mitigation and adaptation strategies are being explored, including conservation tillage, organic matter incorporation, and application of soil amendments such as biochar, bentonite, and zeolite (Abbott and Hinz, 2012; Zhang et al., 2019; Tzanakakis et al., 2021). These measures are often integrated within a system-based approach. The application of organic matter and zeolite has been considered a long-term strategy to improve productivity and sustainability of agricultural cropping systems on sandy soils (Szerement et al., 2021; Tzanakakis et al., 2021; Wu et al., 2024).

Previous research had demonstrated that, in comparison with the application of synthetic fertilizers, the use of organic fertilizers is more effective at promoting profitable crop production, improving soil quality, enhancing carbon sequestration, and alleviating environmental burdens and abiotic stress in general (Liu et al., 2015; Yan et al., 2023; Wu et al., 2024; Cataldo et al., 2024). Recent meta-analysis has revealed that, due to the presence in organic fertilizer of a number of nutrient elements as well as organic matter, substituting a certain proportion of synthetic N fertilizer with organic fertilizer holds the potential to reduce soil emissions of N_2O and CO_2 (Liang et al., 2024; Zheng et al., 2024). However, some studies have indicated that the combined application of organic fertilizer and synthetic N can lead to increased N_2O and CO_2 emissions when compared with the application of synthetic N alone (Jaiswal et al., 2024; Liu et al., 2023). Overall, the impact of organic fertilizer on N_2O and CO_2 emissions remains controversial. Furthermore, our understanding of how organic fertilizer substitution affects GHG emissions in sandy soils is still inadequate. As a result, there is an urgent need to identify alternative methods for reducing emissions and enhancing carbon sequestration, by substituting organic matter for synthetic N fertilizer in sandy soil agroecosystems.

Natural zeolite, a group of aluminosilicate minerals, is extensively used as an eco-friendly soil amendment and a controlled-release fertilizer additive, owing to its exceptional nutrient-adsorption capacity and drought-tolerance enhancement (Ersin et al., 2004; Nakhli et al., 2017; Baghbani-Arani et al., 2020; Szerement et al., 2021). Due to the abundant deposits, high production volume, and low cost of zeolite in China, natural zeolite has been extensively incorporated into various soil types (Szerement et al., 2021). Studies have demonstrated that the incorporation of zeolite can improve the soil's water-holding capacity, reduce the leaching of soil nutrients in arid regions, enhance the water- and fertilizer-use efficiency of crops, and maintain high crop yields (Malekian et al., 2011; Chen et al., 2017; Nakhli et al., 2017; Liu et al., 2024b). Meanwhile, existing evidence suggests that zeolite application in paddy fields can increase grain yield and mitigate N_2O emissions (Sha et al., 2020; Liu et al., 2023). This can be ascribed to the fact that zeolite adsorbs NH_4^+ and retains it within its internal structure. Consequently, the concentration of the reaction substrate for nitrification is reduced, subsequently leading to a decrease in N_2O emissions following N application (Liu et al., 2023; Park et al., 2024). Furthermore, zeolite inhibits the conversion of NH_4^+ to NO_3^-, suppressing the nitrification–denitrification process and thus negatively impacting the generation of N_2O in the soil (Park et al., 2024). Additionally, it has been reported that zeolite can improve soil water retention, which may also influence N_2O emissions, which are strongly positively correlated with soil moisture (Jumadi et al., 2020). These findings highlight the observations that zeolite exerts multiple positive impacts on soil quality, crop yield, and decreases in N_2O emission (Baghbani-Arani et al., 2020; Liu et al., 2023). However, single zeolite application does not affect soil organic matter content (Szerement et al., 2021). To overcome this limitation, the combination of zeolite with organic fertilizers has been found to mitigate the rapid mineralization of carbon and enhance soil carbon sequestration (Latifah et al., 2017). This approach is particularly efficacious in sandy loam soils (Baghbani-Arani et al., 2020), which are characteristically low in clay and organic matter concentrations. Although there has been some research on the effects of zeolite combined with organic fertilizers on soil properties and on emissions of CO_2 and N_2O (Latifah et al., 2017; Baghbani-Arani et al., 2020), our understanding of the impact of the combination on soil properties, soil CO_2 and N_2O emissions, and maize yield in sandy loam soils remains incomplete. Investigating the long-term combined effects of organic fertilizers and zeolite on the soil physicochemical, GHG emissions, and maize yield is crucial for achieving emission reduction and efficiency improvement in sandy loam soils farmlands.

To comprehensively investigate the impacts of co-applying organic fertilizer and zeolite on soil properties, soil CO_2 and N_2O emissions, and maize yield, a 3-year field experiment was conducted on sandy loam soils. We hypothesized that, compared with sole application of inorganic fertilizers, co-applying organic fertilizers and zeolite would enhance the physiochemical and biological properties of sandy loam soils, thereby mitigating GHG emissions and enhancing maize yield and soil fertility in sandy loam soils. The objective of this study was to explore the technical feasibility of sustainably reducing GHG emissions and increasing maize yield in sandy loam soils on the North China Plain through co-application of organic fertilizers and zeolite.

2 Materials and methods

2.1 Field site

The field experiment was conducted in Daxing District (116°28′32″E, 39°58′26″N) in Beijing, North China. The experimental site has a semi-humid temperate continental monsoon climate, with an average annual temperature of 11.9°C, an average annual rainfall of 680 mm, and an altitude of 20.2 m above sea level. The soil is classified as a sandy loam (20% clay, 29% silt, and 52% sand). At the initiation of the field experiment, the following soil properties were determined in homogenized topsoil samples (0–20 cm): soil pH 8.10, electrical conductivity (EC) 75.61 μs cm^{-1}, organic matter 10.32 g kg^{-1}, total nitrogen 0.84 g kg^{-1}, NO_3^--N 6.98 mg kg^{-1}, available phosphorus (AP) 38.01 mg kg^{-1}, and available potassium (AK) 92.74 mg kg^{-1}. The detection methods for the soil physicochemical properties were described by Zhang et al. (2016).

2.2 Experimental design

Five fertilizer treatments were applied, namely: no-fertilizer treatment (control, CK), synthetic fertilizer (SF), organic N fertilizer replacing 30% synthetic N fertilizer (OF), synthetic fertilizer with 15.0 t hm^{-2} zeolite added (ZSF), and organic N fertilizer replacing 30% synthetic N with zeolite added (ZOF) (details presented in Table 1). For the synthetic fertilizer (FTL-30-12-15, Futulai compound fertilizer, Beijing Futulai Compound Fertilizer Co., Ltd., Beijing, China), a compound N: P: K fertilizer (30,12,15) was applied according to local practices as basal fertilizer. The organic fertilizer (FERT-2021-001, Yite organic fertilizer) used in this experiment was commercially produced and sold by Beijing Yite Organic Fertilizer Co., Ltd. (Beijing, China). It was mainly derived from cow manure. The composition of the organic fertilizer consisted of nitrogen (N, 3.3%), phosphorus (P, 1.0%), and potassium (K, 0.7%) and had an organic matter content exceeding 64%. The zeolite (NY-FZ-200, Lingshou Zeolite), sourced from Baidu Zeolite Factory (Shijiazhuang, Heibei, China), had a mean particle diameter of 35 μm.

The five treatments were randomly arranged, and each was replicated four times. Each plot size was 40 m^2 (10 m × 4 m) and was separated from adjacent plots by a 1.0 m-wide buffer row (Supplementary Figure S1). All treatments were designed to have an equal N input of 300 kg N hm^{-2}. All the organic fertilizer, zeolite, and a portion of the synthetic fertilizer were applied as a base fertilizer in the seed bed. They were evenly spread over the field surface and then incorporated into the topsoil (0–20 cm) before planting. The maize (*Zea mays* L.) variety employed in the experiment was 'Jingke 996', with a planting density of 66,500 plants hm^{-2} and a row spacing of 60 cm. The sowing date of maize was set on May 22, and the harvesting date was fixed on September 18 in 2021, 2022, and 2023. When the maize reached the stage of full expansion of the 13th leaf, the remaining N (urea, 46%, F-UR-46-202102) and K (KSO_4, 52%, F-K-52-202101) fertilizers were applied by top-dressing, which were produced and sold by Qian'an Fertilizer Co., Ltd. (Tangshan, Heibei, China).

2.3 Measurements and calculation methods

2.3.1 Greenhouse gas sampling and measurements

During the maize growth periods, from sowing to harvest, in 2021, 2022, and 2023, the CO_2 and N_2O emission fluxes were simultaneously determined *in situ* using the static chamber-gas chromatography (GC) method (Sha et al., 2020). Soil sampling for GHG emission fluxes was carried out using specially made static chambers. Each chamber was composed of a circular PVC base frame (60 cm diameter, 10 cm height), fixed in each plot, with a top cover box (60 cm diameter, 50 cm height). To minimize fluctuations in the internal air temperature, the chambers were covered with a layer of sponge and aluminum foil. The top cover box was equipped with circulating fans to ensure thorough gas mixing. Additionally, electronic thermometers were installed to measure the internal air temperature during sampling. Each base had a well-shaped groove (5 cm in depth) at the top which was filled with water to seal the rim of the chamber during sampling. In general, soil GHG fluxes were determined once each week, and

TABLE 1 Fertilizer amounts applied in different treatments for field trials.

Treatment	Base fertilizer (kg hm^{-2})					Topdressing (kg hm^{-2})	
	Chemical *N*	Organic *N*	P_2O_5	K_2O	Zeolite (*t* hm^{-2})	Chemical *N*	K_2O
CK	0	0	0	0	0	0	0
SF	150	0	120	100	0	150	50
OF	60	90	120	100	0	150	50
ZSF	150	0	120	100	15.0	150	50
ZOF	60	90	120	100	15.0	150	50

sampling was intensified to every two days following irrigation, fertilizer application, or precipitation events. After placing the chamber on pre-fixed bases, four gas samples were taken at each sampling within 30 min (at 0, 10, 20, and 30 min) using a polypropylene syringe (50 mL volume) from 9:30 to 11:00 a.m. These samples were promptly transported back to the laboratory for analysis via gas chromatography. The gas samples (a total of 21,360 CO_2 and 21,360 N_2O in three years) were analyzed using an Agilent 7890B gas chromatograph system (Agilent Technologies, Inc., USA). Further details of measuring GHGs are given in the methodology reported by Jumadi et al. (2020). Concurrent with gas sampling, the soil temperature (Figures 1A–C) at a depth of 10 cm was monitored using a soil thermometer (WH55–405,330, Oriental Chemical and Glass Science and Technology Co., Ltd., Beijing, China); and three soil samples (0–10 cm) were taken from each plot with an auger (3 cm diameter), their moisture contents were evaluated gravimetrically by oven-drying and were expressed as soil water-filled pore spaces (WFPS) using the equation of Pokharel and Chang (2021) (Figures 1D–F).

The *GHG* emission flux (*F*) was calculated using the following Equation 1:

$$F = \rho \times \frac{V}{A} \times \frac{\Delta C}{\Delta t} \times \frac{273}{273 + T} \quad (1)$$

Where *F* represents CO_2 emission fluxes (mg m^{-2} h^{-1}) or N_2O emission fluxes (μg m^{-2} h^{-1}); ρ is the density (mg cm^{-3}) of CO_2 or N_2O under standard conditions; *V* is the volume of the sampling box (m^3); *A* is the soil surface area (m^2) in the sampling base; $\Delta C/\Delta t$ is the gas emission rate; and *T* is the temperature inside the sampling chamber (°C).

Total *GHG* emissions was calculated as follows (Equation 2):

$$M = \frac{\sum(F_{i+1} + F_i)}{2} \times (t_{i+1} - t_i) \times 24 \times 10^{-3} \quad (2)$$

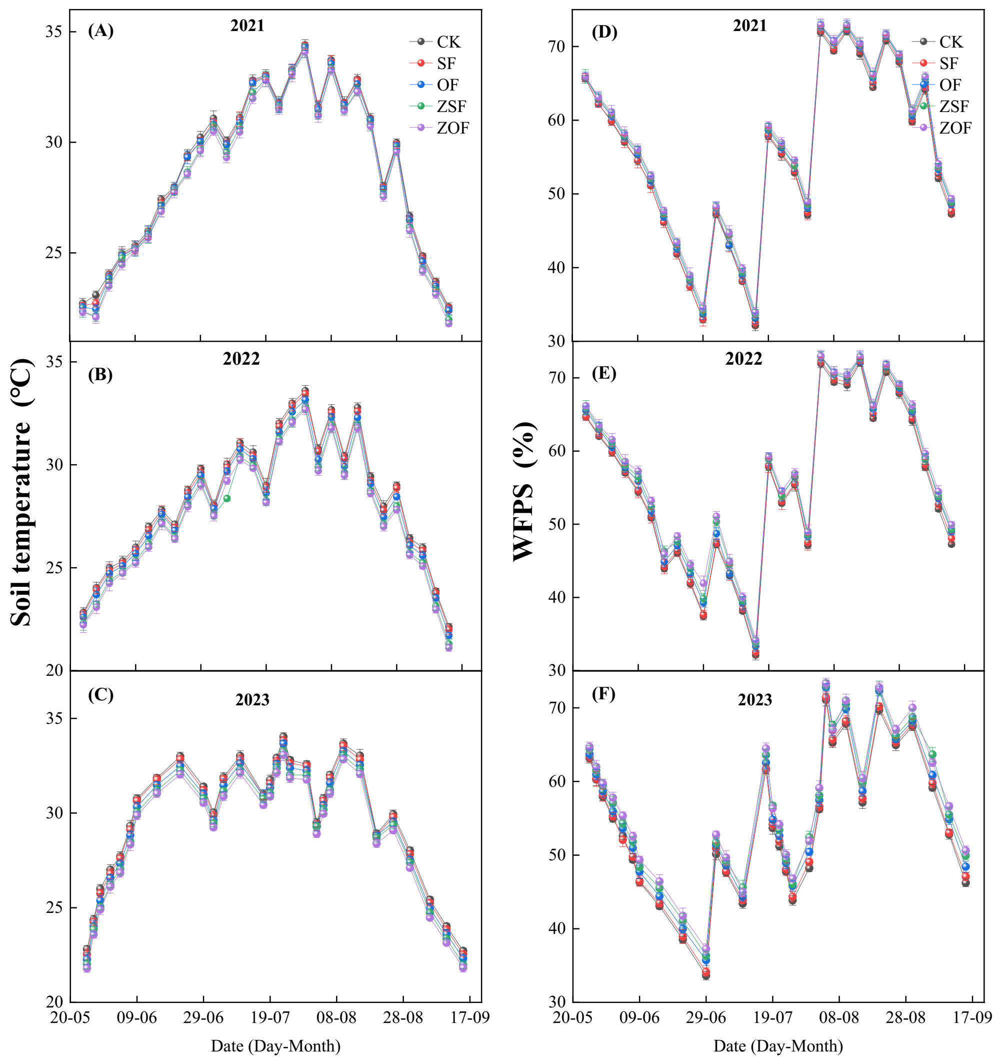

FIGURE 1
Dynamic changes in soil temperature **(A–C)** and water-filled pore space (WFPS) **(D–F)** under different treatments.

Where M is the cumulative of total greenhouse gases (kg hm^{-2}); F_i and F_{i+1} are the gas fluxes determined at the i^{th} and $(i + 1)^{th}$ sampling (CO_2 mg m^{-2} h^{-1} or N_2O μg m^{-2} h^{-1}), respectively; t_i and t_{i+1} are the dates corresponding to the i^{th} and $(i + 1)^{th}$ sampling, respectively.

The global warming potential (*GWP*) was calculated using the following Equation 3:

$$GWP = CO_2 + 298 \times R\left(N_2O\right) \tag{3}$$

Where *GWP* is the comprehensive greenhouse effect of greenhouse gases during the maize growing season, expressed in terms of CO_2-equivalents (kg hm^{-2}); CO_2 refers to the total CO_2 emissions during the maize growing season; and $R(N_2O)$ are the total N_2O emissions during the maize growing season (kg hm^{-2}).

Greenhouse gas intensity (*GHGI*) was calculated as follows (Equation 4):

$$GHGI = GWP / Y \tag{4}$$

Where *GHGI* represents the global warming potential per unit of output (kg CO_2 kg^{-1}); and *Y* represents the maize yield (kg hm^{-2}).

2.3.2 Sampling and analysis of plant samples

At the time of harvest, twenty maize plants were randomly collected from each plot, including both their above-ground and below-ground parts. After collecting, the samples were immediately transferred to the laboratory, dried at 105°C for 30 min to deactivate the enzymes and then dried at 75°C to constant weight, weighed to determine aboveground biomass (AGB) and belowground biomass (BGB). Simultaneously, fifty maize plants were randomly selected, air-dried, shelled, and the kernels weighed to calculate the plot yield.

2.3.3 Soil sampling and detection

Five soil cores at a depth of 0–20 cm were randomly extracted from each plot at the 7-leaf stage, 12-leaf stage, tasseling stage, and after harvest in 2021, 2022 and 2023. These soil cores were then mixed to form a composite sample. The samples (a total of 240 in three years) were then transported to the laboratory and processed further to remove debris and gravel. A portion of them was stored at −20°C for analysis of soil available N and microbial biomass, and a portion of them was air– dried, following sieving through a 0.15 mm sieve for analyses of other available indicators and enzymes activities. The samples at the harvest period (a total of 60 in three years) were analyzed for soil bulk density, soil pH, the concentrations of total organic matter and total nitrogen (TN).

The soil bulk density was determined using the core sampling method; soil pH was determined using a pH meter (water: soil = 2.5:1). The total nitrogen and soil organic carbon (SOC) concentrations were measured by employing an elemental analyzer (Vario EI, Elementar, Langenselbold, Germany). The concentrations of available phosphorus (AP) and available potassium (AK) in the soil were analyzed through ultraviolet spectrophotometry and flame photometry, respectively. Soil NH_4^+-N, NO_3^--N and dissolved organic carbon (DOC) concentrations were detected using a flow analyzer (AA3, Bran + Luebbe, Hamburg, Germany). The activities of soil enzymes β-glucosidase (BG), and nitrate reductase (NR) were assayed using the respective assay kits (Jian Cheng Biological Engineering Research Institute, Nanjing, China). Microbial biomass carbon (MBC) concentration was determined and analyzed using the chloroform fumigation-K_2SO_4 extraction-instrumental analysis method. Microbial biomass nitrogen (MBN) concentration was measured using the chloroform fumigation-K_2SO_4 extraction-total nitrogen determination method. The conversion factors of MBC and MBN were 0.38 and 0.54, respectively (Nunan et al., 1998).

2.4 Statistical analysis

All data analyses were conducted using IBM SPSS Statistics 24.0 software (SPSS Inc., Armonk, NY, USA). The means and standard errors (SE) for each treatment group were calculated. One-way analysis of variance (ANOVA, $p < 0.05$) was employed to detect significant differences in soil physicochemical properties, enzyme activities, microbial biomass, flux and cumulative of CO_2 and N_2O emission, GWP, and GHGI among fertilization treatments, followed by Tukey's post-hoc test. Different lowercase letters represent significant differences between different treatments ($p < 0.05$). Two-way ANOVA was performed to examine the significant effects of year, and treatment, their interaction on maize yield and biomass, emission flux of CO_2 and N_2O, GWP, and GHGI. Figures were generated using Origin 2024 software (OriginLab, Northampton, MA, USA).

3 Results

3.1 Maize yield and biomass

The kernel yield of the control (CK) decreased year by year, since no fertilizer was applied to the CK group. Compared with CK, the kernel yield (Figure 2A), aboveground biomass (AGB) (Figure 2B) and belowground biomass (BGB) (Figure 2C) of maize were all significantly increased in response to fertilizer treatment ($p < 0.05$) (Figure 2), although the differences in these factors across different years were not significant (Supplementary Table S1). The ZOF treatment achieved the highest yield (Figure 2A) and AGB (Figure 2B), significantly greater than those in SF by 14.72–23.61% ($p < 0.05$) over the 3 years, and 8.63–13.33% ($p < 0.05$) in 2022 and 2023, respectively. Compared with SF, the yield was significantly higher by 13.91–15.59% ($p < 0.05$) in ZSF in 2022 and 2023, and by 16.92% ($p < 0.05$) in OF in 2023. Therefore, co-applying organic fertilizer and zeolite (ZOF) demonstrated a more favorable effect on the yield and AGB of maize than did inorganic fertilizer.

3.2 Influence of different fertilizer treatments on greenhouse gas emissions from maize soil

From May 20 to June 15, the dynamics of soil CO_2 emission flux under different treatments exhibited a pattern of initially increasing and then decreasing. Over the 3-year trial period, the OF treatment achieved the highest peak of all the treatments, ranging from 385.30 to 393.54 mg m^{-2} h^{-1}, on either June 3 or 4 (Figures 3A–C). Subsequently, the soil CO_2 emission flux gradually decreased. Notably, after fertilizer application or rainfall, the CO_2 emission flux showed a significant upward surge and peaked 4–6 days later. Compared with the CK, the

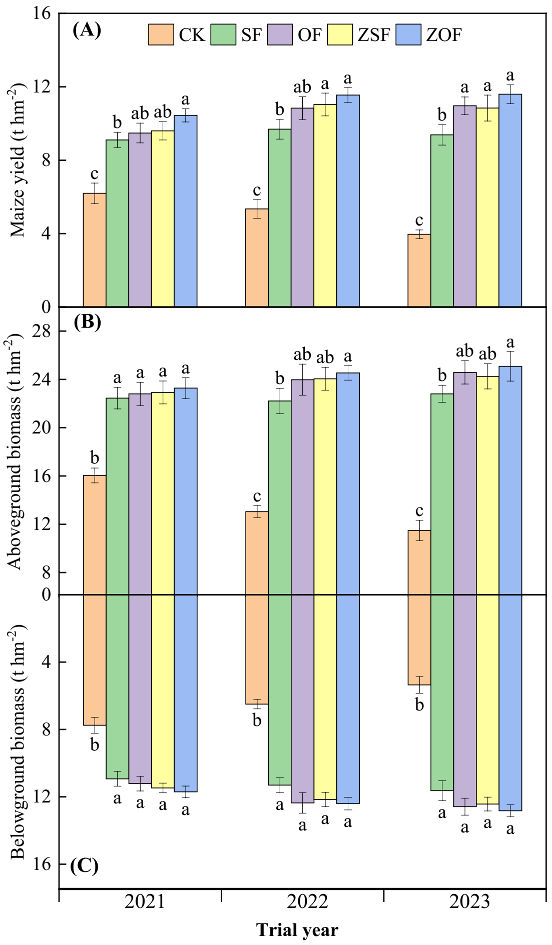

FIGURE 2
The yield **(A)**, aboveground biomass **(B)**, and belowground biomass **(C)** of maize under different fertilizer treatments. Different lowercase letters within a panel and a year represent significant differences between different treatments (p < 0.05). Data represent the mean ± standard error. CK: no-fertilizer; SF: synthetic fertilizer; OF: organic N fertilizer replacing 30% synthetic N fertilizer; ZSF: synthetic fertilizer with 15.0 t hm^{-2} zeolite added; ZOF: organic N fertilizer replacing 30% synthetic with zeolite added.

average soil CO_2 emission flux (Figures 3D–F) and cumulative CO_2 emissions (Figures 3G–I) were significantly increased (p < 0.05) by the fertilizer treatments. Among these treatments, the OF treatment had the highest average CO_2 emission flux and cumulative CO_2 emissions, while the ZSF treatment had the lowest. Specifically, compared with the ZSF treatment, the cumulative CO_2 emissions from the OF treatment were significantly higher by 4.52% (p < 0.05) in 2023. The treatment had a significant impact on soil CO_2 emissions but the year had no significant effect (Supplementary Table S1). Overall, compared with the SF treatment, the OF treatment slightly increased soil CO_2 emissions.

Over the 3-year trial period, the first peak of the soil N_2O emission flux, which ranged from 448.92 to 458.02 μg m^{-2} h^{-1}, was reached on May 29 in the SF treatment; the second peak, ranging from 502.91 to 529.21 μg m^{-2} h^{-1}, occurred within 2–4 days after fertilizer application or rainfall in the SF treatment (Figures 4A–C). Compared with CK, the average soil N_2O emission flux (Figures 4D–F) and cumulative N_2O emissions (Figures 4G–I) were significantly higher (p < 0.05) in the fertilizer treatments. Compared with SF, the average N_2O emission flux in the OF, ZSF, and ZOF treatments were significantly lower by 6.74–8.23%, 6.10–8.79%, and 9.29–11.86% (p < 0.05), respectively; correspondingly, the cumulative N_2O emissions were significantly lower by 9.23–10.85%, 7.59–11.24%, and 12.27–16.06% (p < 0.05), respectively, in 2022 and 2023. The treatment had a significant impact on soil N_2O emissions but the year had no significant effect (Supplementary Table S1). Overall, the ZOF treatment had a greater impact than the other treatments on reducing soil N_2O emissions.

Compared with CK, the total GWP and GWP contributed by N_2O was significantly higher (p < 0.05) in the fertilizer treatments (Table 2). Compared with SF, the GWP contributed by N_2O was significantly lower by 8.45–10.17%, 7.06–10.76%, and 10.93–15.61% (p < 0.05) in OF, ZSF, and ZOF treatments, respectively, in 2022 and 2023; additionally, the total GWP of the ZOF treatment was significantly 4.78% lower (p < 0.05) than that of SF in 2023. Over the 3-year trial period, compared with the SF treatment, the GHGI in the ZSF and ZOF treatments was significantly 6.45–15.31% lower (p < 0.05) and 14.16–21.06% lower (p < 0.05), respectively; the GHGI in the OF treatment was significantly 10.53–13.13% lower (p < 0.05) in 2022 and 2023. Neither the treatment nor the year had a significant impact on GWP, although the treatment had a significant effect on GHGI (Supplementary Table S1). Overall, the ZOF treatment than the other treatments had a more pronounced effect on reducing both GWP and GHGI.

3.3 Impact of different treatments on soil physicochemical properties

Soil pH did not exhibit any significant difference across the various treatments (Figure 5A). Compared with the SF treatment, bulk density was significantly 4.26% (p < 0.05) lower in the ZOF treatment (Figure 5B). Compared with CK, the concentrations of soil organic carbon (Figure 5C), total nitrogen (Figure 5D), dissolved organic carbon (DOC) (Figure 5E), NH_4^+-N (Figure 5F), NO_3^--N (Figure 5G), available potassium (Figure 5H), and available phosphorus (Figure 5I) were significantly higher (p < 0.05) in the fertilizer treatments. Compared with SF, soil NH_4^+-N and NO_3^--N concentrations were significantly lower by 12.27, 9.08 and 10.56, 9.30% (p < 0.05) in the OF and ZOF treatments, respectively, while soil available potassium and phosphorus concentrations were significantly higher by 7.34 and 8.90% (p < 0.05) in the ZOF treatment, respectively. Compared with SF, soil DOC concentration was significantly higher by 15.84, 12.62, and 19.48% (p < 0.05) in OF, ZSF, and ZOF treatments, respectively. Overall, the ZOF treatment had the greatest impact on improving soil physicochemical properties, particularly in terms of available nutrient concentrations.

Compared with CK, the activities of soil enzymes β-glucosidase (Figure 6A) and nitrate reductase (Figure 6B), as well as the concentrations of MBC (Figure 6C) and MBN (Figure 6D), were significantly higher (p < 0.05) in the fertilizer treatments. Compared with SF treatment, the activity of soil β-glucosidase was significantly higher (p < 0.05) by 11.68 and 9.20% in OF and ZOF treatments, respectively, while the activity of nitrate reductase was significantly lower (p < 0.05) by 8.79% in the ZSF treatment. Compared with SF, MBC and MBN concentrations were significantly higher by 8.42 and 11.29% in the ZOF treatment (p < 0.05), respectively. In general, the ZOF treatment significantly increased soil β-glucosidase activities and microbial biomass in the soil.

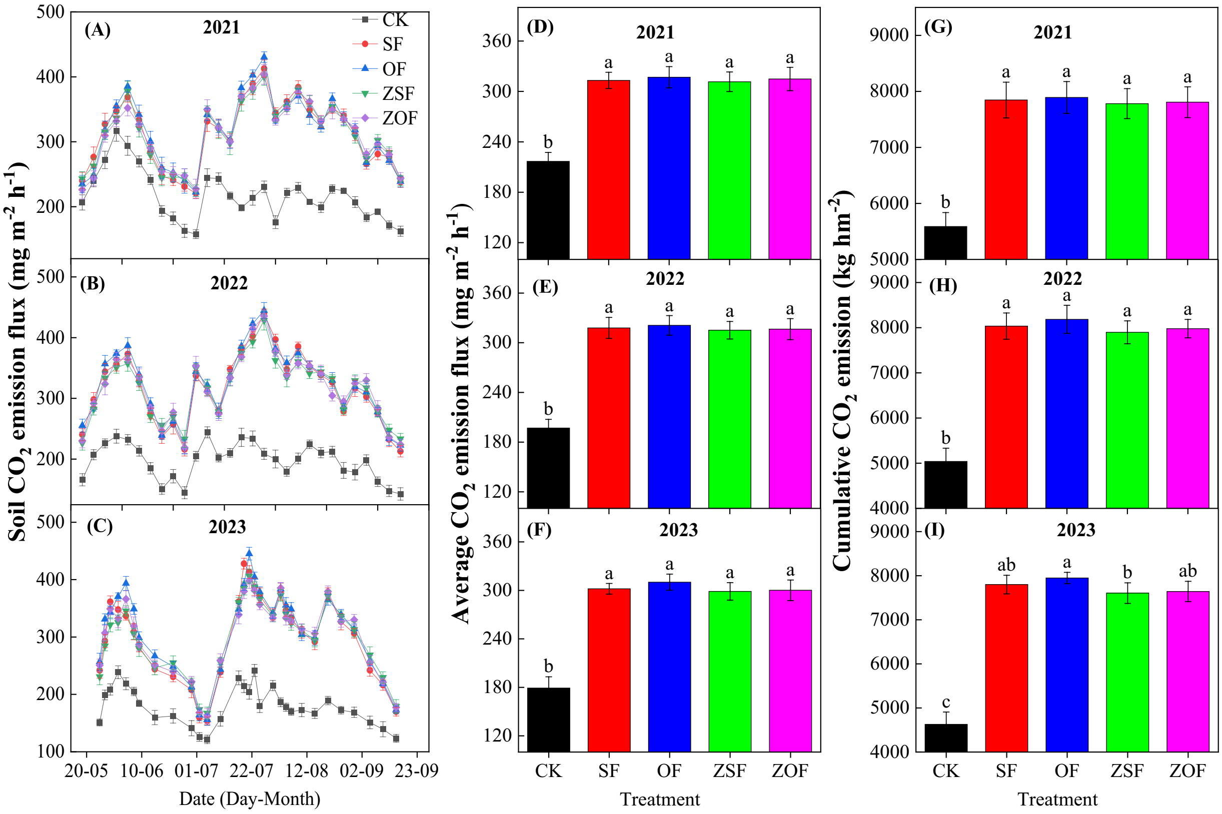

FIGURE 3
Dynamics of CO_2 emission flux **(A–C)**, average CO_2 emission flux **(D–F)**, and cumulative CO_2 emission **(G–I)** in response to different fertilizer treatments. Different lowercase letters within a panel represent significant differences between different treatments (p < 0.05), following ANOVA and the Tukey test. Data are presented as the mean ± standard error.

3.4 Impact of soil factors on soil greenhouse gas emissions and maize yield

Significant positive correlations ($p < 0.05$) were observed between soil CO_2 emissions and several soil parameters, including WFPS, BG activity, and soil concentrations of DOC, OM, MBN, and MBC. Similarly, soil N_2O emissions exhibited significant positive correlations ($p < 0.05$) with soil WFPS, NR activity, and concentrations of NO_3^--N, TN, MBC, and MBN. Furthermore, maize yield was significantly positively correlated ($p < 0.05$) with multiple soil factors such as WFPS, BG activity, and concentrations of DOC, NH_4^+-N, AP, AK, OM, TN, MBC, and MBN. These results suggested that GHG emissions and maize yield in sandy loam soil were closely related to soil moisture, available nutrients, and microbial biomass (Figure 7).

4 Discussion

4.1 Comparison of the effects of different fertilizers on soil CO_2 emissions

Soil CO_2 emissions in farmland primarily originate from the heterotrophic respiration of microorganisms and autotrophic respiration of crop roots (Galic et al., 2019). In the current study, the first peak of soil CO_2 emission fluxes in each fertilizer treatment occurred on June 3 and 4. This peak was ascribed to the soil temperature and humidity becoming more suitable for microbial activity at this stage, so that the nutrients in the base fertilizer were transformed to provide sufficient nutrition for microorganisms, thereby facilitating their heterotrophic respiration. Notably, the soil CO_2 emission fluxes in the OF treatment were higher than those in the SF and ZSF treatments during this stage. This was because a large quantity of exogenous organic carbon from organic fertilizer was incorporated into the soil and directly served as the respiratory substrate for microorganisms, promoting soil CO_2 emissions (Wang et al., 2022; Chaker et al., 2023; Jaiswal et al., 2024). By mid-June, as the easily degradable organic substances in the organic fertilizer were being consumed, the soil CO_2 emission fluxes under the OF treatment decreased and were no longer significantly different from those under the SF treatment. During the middle growth period of maize, a secondary peak in soil CO_2 emission fluxes occurred in each treatment. This might be because the abundant precipitation and relatively high soil temperatures (Supplementary Figure S2) during this period enhanced the activity of soil microorganisms. Particularly after the top-dressing of urea in late July, the concentration of available N in the sandy soil increased rapidly, providing sufficient N for the growth of both plants and microorganisms. At this point, the respiration of maize roots was intense, thus accelerating the soil CO_2 emission fluxes (Oraegbunam et al., 2022; Liu et al., 2024a).

Throughout the maize growing season, compared with SF, OF slightly increased the cumulative soil CO_2 emissions, which was consistent with the research results of Jaiswal et al. (2024) and Liu et al.

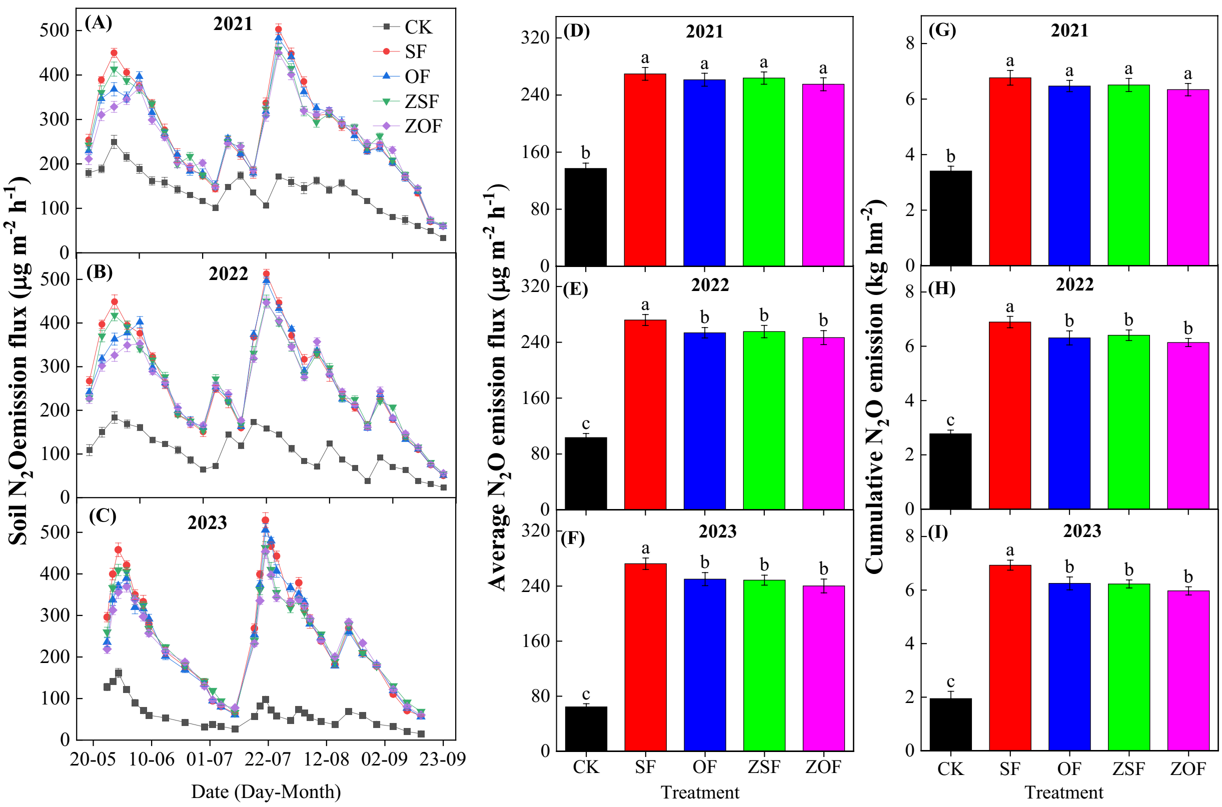

FIGURE 4
Dynamics of N_2O emission flux **(A–C)**, average N_2O emission flux **(D–F)**, and cumulative N_2O emission **(G–I)** in different fertilizer treatments. Different lowercase letters within a panel represent significant differences between different treatments ($p < 0.05$), following ANOVA and Tukey test. Data represent the mean ± standard error.

TABLE 2 The global warming potential (GWP) and greenhouse gas intensity (GHGI) in different treatments.

Time	Factor	CK	SF	OF	ZSF	ZOF
2021	GWP contributed by N_2O (kg CO_2 hm^{-2})	1015.32 ± 47.34 a	2016.55 ± 65.03 a	1930.89 ± 58.73 a	1945.30 ± 49.82 a	1904.37 ± 50.99 a
	Total GWP (kg CO_2 hm^{-2})	6603.45 ± 269.23 b	9863.78 ± 327.67 a	9820.24 ± 293.69 a	9721.55 ± 279.02 a	9697.55 ± 282.14 a
	GHGI (kg CO_2 kg^{-1})	1.07 ± 0.004 a	1.08 ± 0.005 a	1.04 ± 0.004 a	1.01 ± 0.003 b	0.93 ± 0.004 b
2022	GWP contributed by N_2O (kg CO_2 hm^{-2})	827.79 ± 62.82 c	2053.73 ± 60.22 a	1880.17 ± 59.11 b	1908.81 ± 57.93 b	1829.21 ± 44.94 b
	Total GWP (kg CO_2 hm^{-2})	5867.56 ± 313.91 b	10088.57 ± 304.46 a	10064.95 ± 329.19 a	9806.81 ± 271.32 a	9807.55 ± 217.87 a
	GHGI (kg CO_2 kg^{-1})	1.10 ± 0.004 a	1.04 ± 0.005 a	0.93 ± 0.004 b	0.89 ± 0.004 b	0.85 ± 0.004 b
2023	GWP contributed by N_2O (kg CO_2 hm^{-2})	580.23 ± 44.38 c	2084.43 ± 55.73 a	1872.41 ± 81.59 b	1860.10 ± 70.37 b	1758.97 ± 45.50 b
	Total GWP (kg CO_2 hm^{-2})	5209.22 ± 283.01 c	9873.42 ± 216.61 a	9820.13 ± 168.72 ab	9464.71 ± 232.09 ab	9401.08 ± 233.88 b
	GHGI (kg CO_2 kg^{-1})	1.31 ± 0.004 a	1.03 ± 0.005 b	0.90 ± 0.004 c	0.87 ± 0.005 c	0.81 ± 0.004 c

Different lowercase letters between treatments within a row represent significant differences between treatments ($p < 0.05$). Data represent the mean ± standard error.

(2024a). The underlying mechanisms for increased CO_2 emissions under OF treatment can be attributed to three key factors. First, the part-replacement of synthetic fertilizer by organic fertilizer increased the concentration of active organic carbon (from organic matter) in the sandy loam soil. This provided an adequate concentration of substrate for microbial respiration, promoted the metabolic activities of microorganisms, and directly increased CO_2 emissions (Bhunia et al., 2021; Delucena et al., 2023). The positive correlations observed between microbial biomass carbon, soil β-glucosidase activity, and soil CO_2 emissions observed in this study supported this mechanism. Second, organic fertilizers application improved soil fertility, which in turn promoted the growth and metabolism of maize roots. As a result, the CO_2 emissions from root respiration increased. The increase in belowground biomass observed in this study also supported this

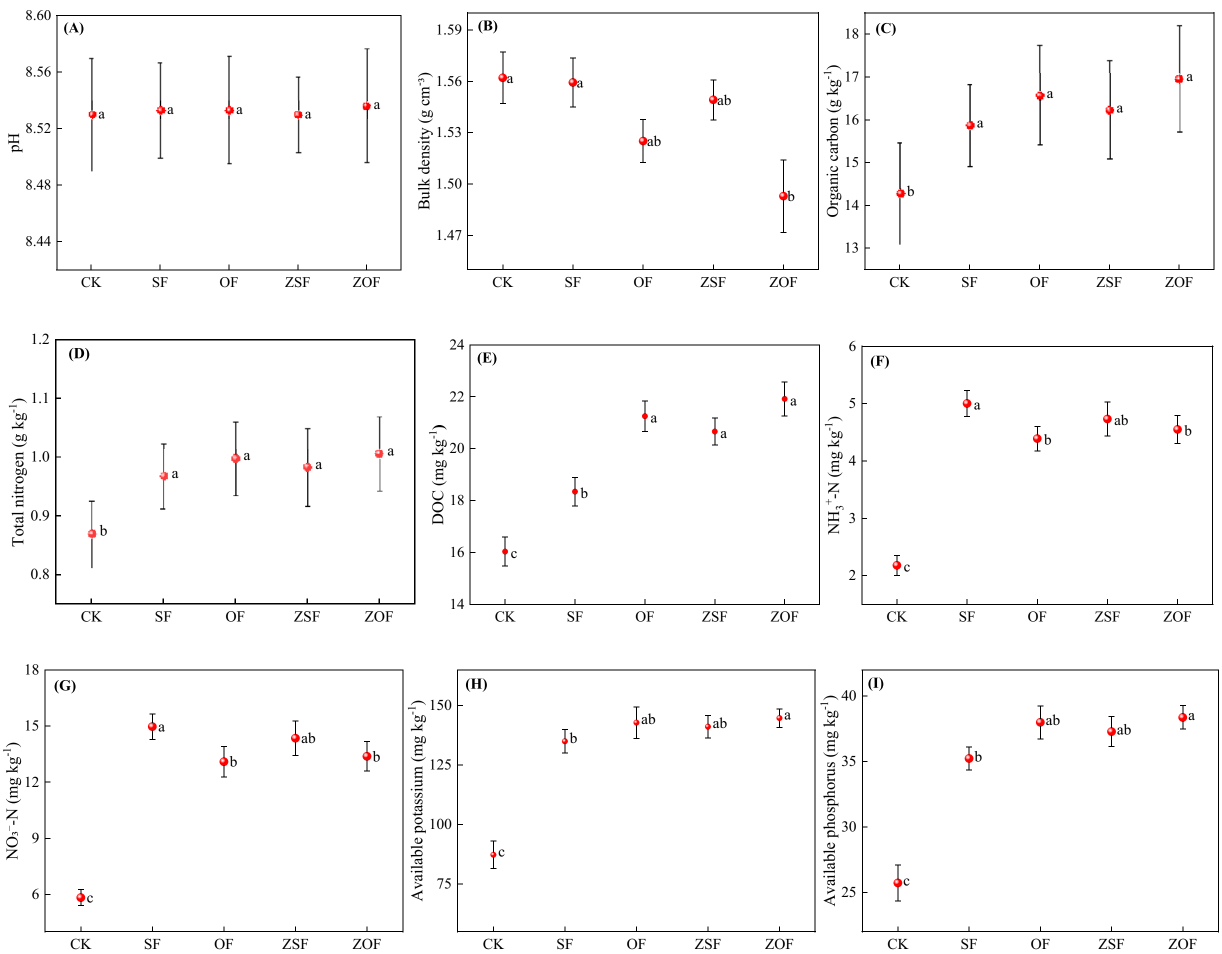

FIGURE 5
Soil physicochemical properties following different fertilizer treatments. The pH **(A)**, bulk density **(B)**, concentrations of organic carbon **(C)**, total nitrogen **(D)**, DOC **(E)**, NH_4^+-N **(F)**, NO_3^--N **(G)**, available potassium **(H)**, and available phosphorus **(I)**. Different lowercase letters within a panel represent significant differences between different treatments (p < 0.05), following ANOVA and the Tukey test. Data represent the mean ± standard error.

hypothesis (Bhunia et al., 2021; Yan et al., 2023). Third, the introduction of exogenous organic matter into sandy loam soil accelerated the decomposition of the original soil organic matter, triggering a positive priming effect. Collectively, these mechanisms contributed to an increase in soil CO_2 emissions under the OF treatment (Chaker et al., 2023).

In the current study, compared with the SF treatment, the ZSF treatment reduced soil CO_2 emissions to a certain extent, while the ZOF treatment had an insignificant impact on soil CO_2 emissions. This phenomenon was ascribed to the following reasons. First, the application of zeolite powder with a small particle size (35 μm diameter) to the sandy loam soil increased the soil bulk density and decreased the porosity. To some extent, this led to a reduction in soil oxygen concentration, resulting in a decrease in the available oxygen within the soil. Consequently, the respiration rate of microorganisms and roots was inhibited, thereby reducing CO_2 emissions (Liu et al., 2024a). However, zeolite addition had no significant effect on soil bulk density in clay soils (Ersin et al., 2004; Obalum and Obi, 2010), moreover, the oxygen diffusion coefficient in clay soils is significantly lower than that in sandy soils, which inherently inhibits aerobic respiration. Therefore, zeolite application that reduces soil CO_2 emissions may be more suitable for sandy soils. Second, the sandy loam soil had a relatively low clay content, and the cohesion among soil particles was poor. As a result, it was challenging to form large aggregates and hence large pores to achieve soil aeration. The application of zeolite and exogenous organic matter could directly or indirectly supply a cementing agent for soil aggregates. This promoted the formation of large aggregates and enhanced the stability of soil aggregates through physical protection, thus reducing the decomposition of soil carbon (Abdalla et al., 2022; Hei et al., 2024). In addition, the application of zeolite not only decreased soil water evaporation but also increased the soil water-binding capacity (Nakhli et al., 2017). Given that CO_2 has a high solubility in water, the application of zeolite decreased the diffusion of CO_2 to the soil surface (Abdalla et al., 2022).

4.2 Comparison of the effects of different fertilizers on soil N_2O emissions

Because soil N_2O generation and emission are under the regulation of N fertilizer management strategies, a rationalized N

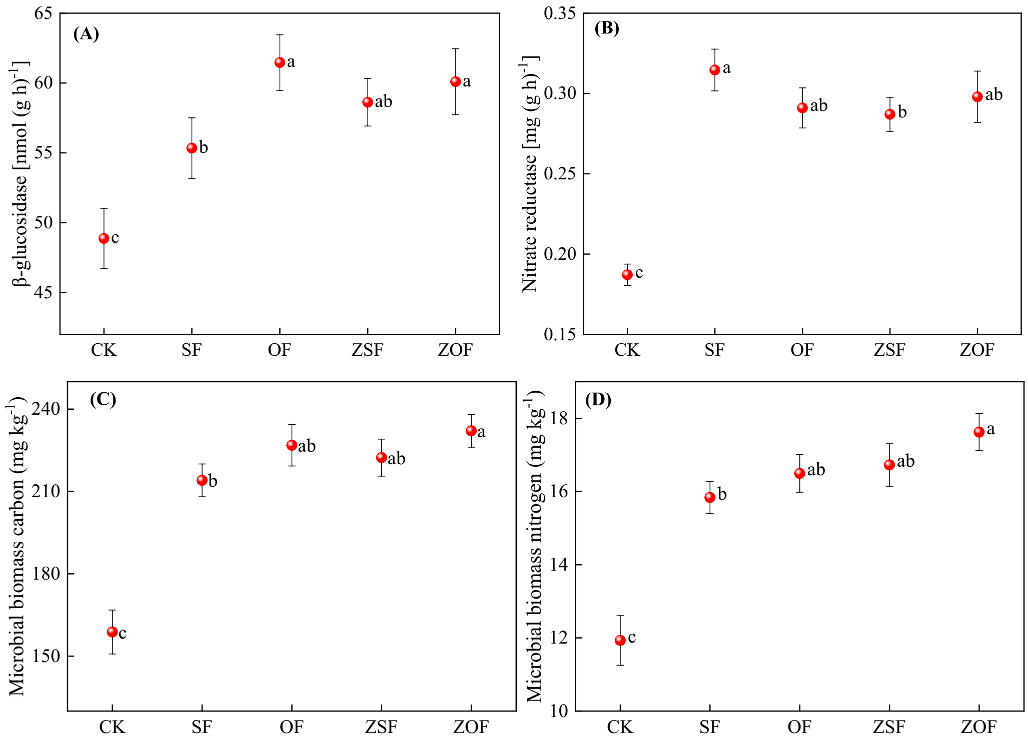

FIGURE 6
Soil enzyme activities and microbial biomass in different fertilizer treatments. β-glucosidase activity **(A)**, nitrate reductase activity **(B)**, microbial biomass carbon concentration **(C)**, and microbial biomass nitrogen concentration **(D)**. Different lowercase letters within a panel represent significant differences between different treatments (p < 0.05), following ANOVA and the Tukey test. Data represent the mean ± standard error.

fertilizer approach could effectively curtail soil N_2O emissions (Wu et al., 2024). In the present study, the peak value of soil N_2O flux occurred following N fertilizer application, with the highest peak occurring under the SF treatment (Figure 4). Application of synthetic N fertilizer typically resulted in an excess of soil inorganic N. This surplus provided abundant substrates for both nitrification and denitrification, two complementary microbial processes in agricultural soils that generate N_2O (Shu et al., 2021; Chataut et al., 2023). Our research revealed that, compared with SF, the OF treatment significantly reduced soil N_2O emissions by 9.23–10.85% (Figure 4), indicating that replacing 30% of synthetic fertilizer N with organic fertilizer N mitigated soil N_2O emissions in a sandy loam soil. This finding aligned with results from previous research in loam and clay soils, which showed that substitution with organic N had a positive impact on soil quality and could reduce N_2O emissions (Liang et al., 2024; Park et al., 2024). Several mechanisms can account for the decrease in N_2O emissions in response to organic fertilizer N substitution. First, soil NO_3^- and NH_4^+, serving as key substrates and reactants in nitrification and denitrification processes, play pivotal roles in regulating N_2O fluxes (Wu et al., 2022). Organic N fertilizer part-substitution for synthetic N fertilizer reduced soil NO_3^- and NH_4^+ concentrations compared with sole inorganic N fertilizer application (Figure 5), a finding which was similar to the results of Wu et al. (2024). Generally, organic fertilizers predominantly supply organic N, which is gradually converted to inorganic N through N mineralization, then the mineral N is quickly absorbed by plants (Jaiswal et al., 2024). As a result, organic substitution diminishes the supply of mineral N substrates for nitrifying and denitrifying bacteria, thereby reducing N_2O emissions. This phenomenon is further supported by the positive correlations between N_2O emissions and soil NO_3^- and NH_4^+ concentrations observed in both the current study (Figure 7) and prior research (Xie et al., 2024).

Second, organic fertilizers release N slowly after the decomposition of organic matter, limiting the risk of N being converted into N_2O, N_2, or ammonia (Shu et al., 2021). Moreover, organic fertilizers can enhance the retention of available N in the soil, facilitating its uptake by plants and minimizing excessive gaseous N losses (Cheng et al., 2022; Liang et al., 2024). Finally, organic fertilizers can promote the reduction of N_2O to N_2 by enhancing electron flow in denitrification, especially in low-NO_3^- soils (Tang et al., 2024). In the present study, the soil NO_3^- concentration was relatively low in the OF treatment, which led to the reduction of N_2O emissions.

The results indicated that, compared with the SF treatment, the peak values of N_2O emission fluxes and cumulative N_2O emissions were lower in zeolite application treatments (ZSF and ZOF) than in no-zeolite treatments. This suggested that the application of zeolite mitigated soil N_2O emissions in sandy loam soils, a conclusion that aligned with research findings from paddy soils (Sha et al., 2020). Several underlying factors can account for this phenomenon. Firstly, due to its high adsorption capacity, zeolite can "dampen the peaks" of soil nutrients following N fertilizer application. It reduces the concentrations of reaction substrates (NO_3^- and NH_4^+) for soil nitrification–denitrification processes following N application. As a result, zeolite mitigates the peak values of soil N_2O generation and emission after the application of both base and top-dressing N fertilizers (Ippolito et al., 2011; Liu et al., 2024a). Second, zeolite can

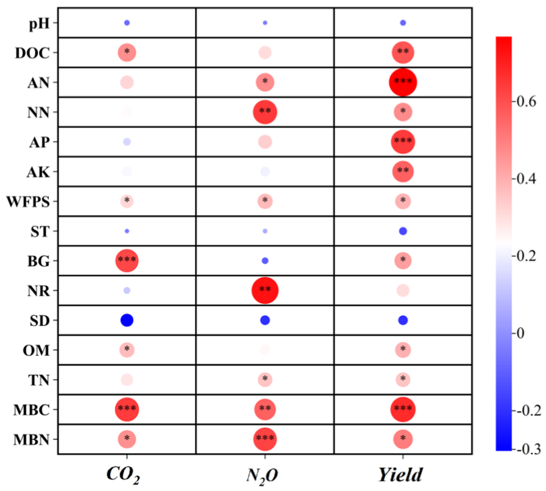

FIGURE 7
Pearson's correlation analysis between soil greenhouse gas emissions, maize yield, and soil physicochemical properties. DOC: dissolved organic carbon; AN: NH_4^+-N; NN: NO_3^--N; AK: available potassium; AP: available phosphorus; WFPS: water-filled pore space; ST: soil temperature; BG: soil β-glucosidase activity; NR: nitrate reductase activity; SD: soil bulk density; OM: organic matter concentration; TN: total nitrogen concentration; MBC: microbial biomass carbon concentration; and MBN: microbial biomass nitrogen concentration. Red = positive, blue = negative *r* values; *$p < 0.05$; **$p < 0.01$; $p < 0.001$.

bind NH_4^+ within its pore structure, providing a long-lasting fertilizer effect. Moreover, the small channels within zeolite can prevent nitrifying bacteria from accessing the bound NH_4^+, thus inhibiting the nitrification of NH_4^+. This effectively reduces the loss of active N (Jumadi et al., 2020). Thirdly, zeolite has a high water-holding capacity. It can regulate water flow within soil pores and mitigate N_2O emissions by reducing the nitrification process in the soil (Zheng et al., 2024). Lastly, the application of zeolite can effectively suppress nitrate reductase activity (Figure 6), a key enzyme in denitrification pathways, thereby reducing N_2O emissions (Tzanakakis et al., 2021).

The application to soil of zeolite significantly mitigated soil N_2O emissions primarily through two integrated mechanisms when organic fertilizer replaced 30% of the synthetic N in sandy loam soil (Figures 4, 5). First, the N release rate from the organic fertilizer, in combination with zeolite's capacity to adsorb part of NH_4^+-N and NO_3^--N, prevented the concentrations of inorganic N in the soil from reaching excessively high levels. This phenomenon reduced the substrates available for nitrification and denitrification, thereby decreasing the peak value of N_2O emission flux and N_2O cumulative emissions in the ZOF (zeolite-organic-synthetic fertilizer) treatment (Figure 4). The increase in soil organic N, which was introduced through the application of organic fertilizer, can promote the assimilation of organic N by soil microbial activity, immobilize more N by microbial activity, and reduce the amount of N available for the production of N_2O (Nakhli et al., 2017; Cheng et al., 2022). This present study further confirmed that the ZOF treatment significantly increased the MBN concentration (Figure 6); during the maize growing season, the N_2O fluxes were significantly negatively correlated with MBN concentration (Figure 7) (Zheng et al., 2024). Second, zeolite enhanced the soil aggregate structure, while organic fertilizers increased soil organic matter and microbial activities. Together, they created a favorable soil environment for crop growth and microbial activity, increased the activity of denitrifying enzymes, enhanced the reduction of NO_3^- to N_2, and inhibited the production and emission of N_2O (Park et al., 2024).

Soil temperature and moisture are also pivotal factors influencing N_2O emissions (Wu et al., 2022; Jaiswal et al., 2024). N_2O emissions were substantially higher during the middle stage of the maize growth period compared with the early stage. This difference can be mainly attributed to the higher soil temperature and moisture levels in the middle stage of maize growth (Figure 1 and Supplementary Figure S2). These elevated conditions accelerate the N-cycling process, thereby enhancing N_2O production (Jumadi et al., 2020; Zhong et al., 2021). When water acts as a limiting factor, the ZOF treatment increased the N_2O emission flux during this stage, due to an increase in the WFPS content (Supplementary Figure S3). Notably, WFPS exhibited a significant positive correlation with soil N_2O emissions, as reported by Fan et al. (2024).

4.3 Comparison of the effects of different fertilizers on soil fertility

Soil quality is a multifaceted indicator that reflects the soil's potential to sustain its ecological functions, which depends on the interplay of physical, chemical, and biological properties (Li et al., 2022). The present study demonstrated that the ZOF treatment augmented the concentrations of soil organic matter, dissolved organic carbon, available potassium, and available phosphorus in sandy loam soil. Additionally, it increased the activities of soil *β*-glucosidase and the concentrations of microbial biomass carbon and nitrogen, while reducing the soil's bulk density. This finding is largely consistent with previous research, indicating that, when the organic fertilizer, replacing 30% of the synthetic fertilizer N, and zeolite were applied together, soil quality was improved (Park et al., 2024).

The soil treated with organic fertilizer and zeolite co-application was also more effective at retaining soil nutrients. Organic fertilizers are enriched with organic matter containing various nutrients and can provide a rich source of nutrients to the soil. The slow-release nature of nutrients from organic fertilizers ensures a continuous nutrient supply (Hei et al., 2024; Wu et al., 2024). Zeolite, with its distinctive porous structure and high cation-exchange capacity, can adsorb and store nutrient ions such as NH_4^+, NO_3^-, K^+, PO_4^{3-}, and Mg^{2+}, preventing these nutrients from being leached away by rainwater or irrigation (Latifah et al., 2017; Baghbani-Arani et al., 2020; Ferretti et al., 2024), and minimizing NO_3^- losses in sandy loam soil of North China (Li et al., 2022). Consequently, the combined application of zeolite and organic fertilizer further bolsters the soil's nutrient-retention capacity.

The co-application of organic fertilizer and zeolite can enhance the aggregation of soil particles (Lin et al., 2025). The organic colloidal substances in organic fertilizers can interact with zeolite and bind soil particles together, forming more stable aggregates. The activity of soil microorganisms is enhanced under the ZOF treatment. Organic fertilizers provide labile carbon sources and energy for microorganisms, spurring their activity and reproduction, and increasing microbial biomass carbon and nitrogen (Liu et al., 2024b). Simultaneously, during the decomposition of organic fertilizers and the utilization of nutrients adsorbed by zeolite, the metabolic activities of microorganisms increase. This leads to an increase in the activities of soil enzymes, such as β-glucosidase and nitrate reductase activity, and these enzymes play a crucial role in the transformation of soil carbon and nitrogen nutrients (Yang et al., 2019).

4.4 Comparison of the effects of different fertilizers on maize yield, GWP, and GHGI

Stable or increased production is one of the most effective ways to evaluate agricultural practices (Wang et al., 2024). Previous studies have confirmed that the reasonable application of organic fertilizers and the addition of zeolite are important management strategy for increasing crop yields in sandy soils (Liu et al., 2024c; Zheng et al., 2024). The current study obtained similar results, demonstrating that the co-applied organic fertilizer and zeolite could significantly enhance maize yield, primarily as a result of their ability to provide sufficient nutrients and foster a suitable growth environment for maize plants. Previous studies have confirmed that rationalized application of organic fertilizers, in conjunction with the addition of zeolite, serves as a pivotal management strategy for enhancing crop yields in sandy soil (Liu et al., 2024c; Zheng et al., 2024), underscoring their applicability across temperate sandy agroecosystems.

When applied to the soil, zeolite exhibits remarkable properties. It can adsorb a substantial quantity of water and nutrient ions due to its microporous structure and high cation exchange capacity, thereby minimizing water and nutrient losses that typically occur after fertilizer application. Moreover, when the concentrations of water and nutrients in the soil are relatively low, zeolite slowly releases the adsorbed substances (Tarkalson and Ippolito, 2011; Zheng et al., 2024). Through this dynamic adsorption-release balance of zeolite, the various nutrient elements from organic fertilizers are gradually released into the soil, ensuring the continuous supply of available water and nutrients in sandy soil, mitigating the negative impacts of water and nutrient deficiency stress on maize yield, and improving water- and fertilizer-use efficiency to a certain extent (Omar et al., 2018; Liu et al., 2024c; Wang et al., 2024). In addition, a relatively well-developed root system directly augments the plant's capacity to take up water and soil nutrients, including NH_4^+, NO_3^-, available phosphorus, and available potassium (Baghbani-Arani et al., 2020; Liu et al., 2023). In addition, such a robust root system effectively enhances the transport efficiency of nutrients and water from the soil to the shoots, increasing leaf relative water content by 12% and photosynthetic rate by 15%, consequently increasing nutrient accumulation and aboveground biomass (stems and leaves) and grain yield of maize (Park et al., 2024). Furthermore, appropriate concentrations of soil water and nutrients stimulate microbial biomass and shift community composition, and reduce nutrient loss by carbon and nitrogen fixation by microbes, enhancing the utilization efficiency of water and nutrients by maize and ultimately contributing to an increase in maize yield (Latifah et al., 2017; Park et al., 2024). In conclusion, the co-addition of organic fertilizer (replacing 30% of the synthetic N fertilizer) and zeolite represented an effective approach to improving maize yield in sandy loam soil and promoted the sustainable production of such farmland. However, the optimal ratio of the application of zeolite to organic fertilizer for the improvement of loamy sandy soil still requires systematic investigation.

In the current study, the GWP was calculated based on the fluxes of two GHGs, CO_2 and N_2O, expressed in terms of CO_2-equivalents, following the methodology proposed by Chataut et al. (2023). Consistent with previous research (Liu et al., 2024b; Xie et al., 2024), our findings demonstrated that the OF and ZSF treatments significantly reduced the contribution of N_2O emissions to GWP during the maize growing season (Table 2); this may be because both the replacement of 30% of synthetic N fertilizer by organic fertilizer and the application of zeolite inhibited N_2O emissions (Figure 4). Additionally, the ZOF treatment significantly decreased the total GWP in 2023. This is likely because co-application of organic fertilizer and zeolite inhibited both N_2O and CO_2 emissions. The GHGI depends on the grain yield of maize and the total greenhouse gas emissions from the soil and is a variable which can better reflect the relationship between economic and environmental benefits in agricultural systems (Zhang et al., 2019). Compared with the SF treatment, the GHGI was lower in the OF, ZSF, and ZOF treatments during the 3 years of trials (Table 2), and was due to the increase in maize yield (Figure 2) and decrease in the N_2O-related contribution to GWP. The present research indicated that the ZOF treatment had the most pronounced effect in reducing CO_2 and N_2O emissions and improving maize production by promoting soil physicochemical and biological properties in sandy loam soil, thus confirming our initial hypothesis. The organic N fertilizer replacing 30% synthetic N with 15.0 t hm^{-2} zeolite added (ZOF) hold great promise for reducing GHG emissions, enhancing maize yields, and improving soil quality in the sandy loam soils of the North China Plain. Overall, our research has not only provided invaluable insights into the sustainable development of sandy loam farmlands, but also offered a technical basis for yield enhancement and GHG emission reduction (particularly N_2O) in vegetable cultivation with high fertilizer requirements in this region. However, in farmlands with other soil types in temperate regions, it is essential to adjust the application scheme of zeolite-organic amendments according to local soil types to achieve the synergistic objectives of carbon sequestration and yield enhancement, complemented by appropriate agricultural extension programs to enhance regional climate adaptability.

5 Conclusion

Compared with the control, fertilization treatments significantly enhanced maize yield. Notably, the yield-increasing effect of organic fertilizer substitution and zeolite application became progressively more pronounced over time. Both the ZOF and ZSF treatments gradually increased maize yields over time and were less prone to generating soil N_2O emissions than the SF treatment. Compared with the SF treatment, the ZOF treatment significantly mitigated GHG emissions, especially N_2O emissions, while enhancing maize yield and soil quality in sandy loam soils. The increased maize yield in the ZOF treatment could be attributed to increased concentrations of soil moisture, available potassium and available phosphorus, and microbial biomass. The reduced N_2O emissions from the maize field under the ZOF treatment were achieved by decreasing soil NH_4^+-N and NO_3^--N concentrations. The ZOF treatment significantly mitigated GHGI due to lower GWP and higher yield than the SF treatment. Our findings concluded that the ZOF treatment was optimal for achieving stable yield and reductions in GHG emissions based on comprehensive crop yield and environmental benefits.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

XW: Writing – original draft, Writing – review & editing, Data curation. JW: Writing – review & editing, Methodology, Conceptualization. PY: Software, Writing – original draft, Formal analysis. QZ: Writing – original draft, Data curation, Supervision. QS: Writing – review & editing, Project administration. DL: Project administration, Funding acquisition, Writing – review & editing.

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Conflict of interest

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1614139/full#supplementary-material

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