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Field slurry application in northeastern China for reducing greenhouse gases and ammonia emission

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KEYWORDS

Ammonia, emission reduction, greenhouse gas emission, slurry application

HIGHLIGHTS

- Pre-acidified slurry (pH 6) reduced NH_3 emission by 42%.
- Partial slurry resulted in lower NH_3 emission compared to full slurry application.
- Drip irrigation reduced N_2O and NH_3 more effectively than sprinkler irrigation.
- N_2O emission increased after precipitation in slurry application.

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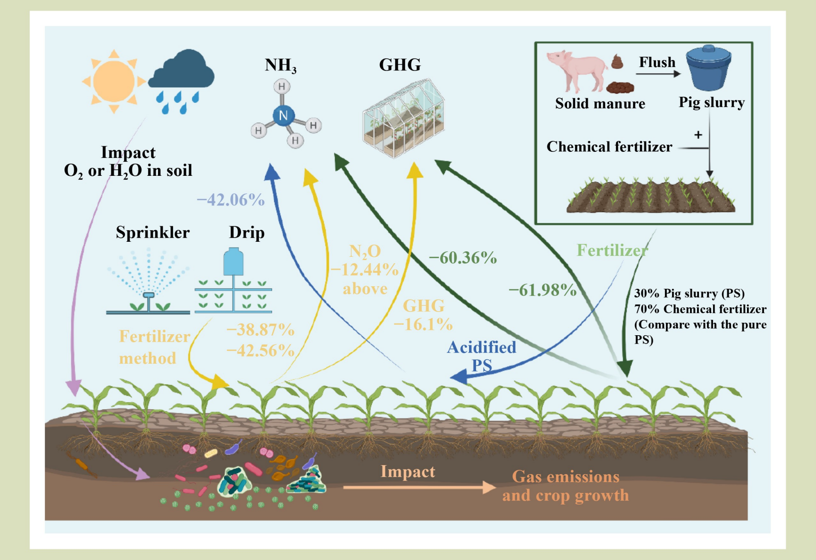
GRAPHICAL ABSTRACT



ABSTRACT

Rapid development of the pig industry in China has led to numerous challenges in managing livestock manure and slurry. Field application of slurry has proven to be an economical, effective and environmentally beneficial approach to sustainable resource recycling globally. However, China remains largely dependent on fertilizer inputs from mineral sources, with limited adoption of slurry application practices. A common challenge with slurry field application is its typically higher emission of ammonia and greenhouse gases (GHGs) compared to mineral fertilizers. This work investigated selected treatments with specific ratios of pig slurry and mineral fertilizers aimed at reducing the use of mineral fertilizers and emission following basal fertilizer application and topdressing after maize planting specifically, the ratios of pig slurry included 30%, 50% and 100%. The methods of fertilizer application involved a comparison of acidified versus non-acidified pig slurry for field application, as well as a comparison between sprinkler and drip irrigation. The results showed that replacing 30% of mineral fertilizers with pig slurry (RC30) reduced total GHG emission by 62% and NH_3 emission by 60.4% compared to a full slurry substitution during field application. Meanwhile, the RC30 group recorded the lowest total NH_3 emission, totaling 5.08 $kg\cdot ha^{-1}$, among all treatments using pig slurry. The acidification of pig slurry significantly reduced NH_3emission, decreasing them by 42.1% compared to the direct application of untreated pig slurry. Drip irrigation proved to be more effective in reducing total GHG emission compared to sprinkler irrigation. Drip irrigation reduced NH_3emission by 38.9%–42.6%, N_2O emission by 12.4%–18.6%, and GHG emission by 21.5%–34.7%. In summary, this study demonstrated that replacing 30% of mineral fertilizers with pre-acidified pig slurry, combined with drip irrigation, reduced GHG and NH_3 emission.

1 Introduction

With the improvement of global living standards, livestock and poultry farming have increased significantly, especially in China. China's livestock industry is gradually moving towards intensification and large scaling, currently accounting for over 40% of the global pork production[1]. For example, multilayer farming is emerging in agriculture. The large-scale pig farming inevitably raises serious concerns about the management of manure slurry and wastewater[2,3]. Agriculture is characterized by low added value and high sensitivity to costs, requiring economically efficient treatment methods to promote recycling. After simple treatment, using the manure and slurry from pig farms for field application is usually a cyclic and cost-effective method, especially considering China's economic situation as a developing country[4]. This method relies on with the principles of the circular economy both in China and globally, contributing to the achievement of carbon neutrality goals. Currently, China's land cultivation heavily relies on fertilizers to provide nutrients to crops, leading to soil compaction and negative impacts on the land's original ecological functions. As a result, modern agriculture has moved to using a combination of organic and mineral fertilizers[5]. Using animal manure as organic fertilizer for field application is, in fact, an economical, straightforward and resource-recycling method. This can enhance soil nutrients, improve soil structure and promote crop growth due to its high nitrogen and phosphorus content[6-8]. However, numerous studies indicate that although slurry has a higher water content and lower nutrient concentration compared to manure, its use can still offer benefits in field applications. The urinary nitrogen in slurry is notably higher than in manure[9], which consequently leads to relatively higher NH_3emission. However, careful coordination with inorganic fertilizers is required to meet the yield requirements of various crops.

The typical process of using manure and slurry for field application inevitably leads to increased NH_3 emission, nitrogen loss and greenhouse gas (GHG) emission[10–12]. Therefore, it is crucial to strike a balance between meeting the nutrient requirements of crops and mitigating the environmental impact. Different fertilizer application ratios and methods are crucial for GHG and NH_3 emission during plant growth. Therefore, it is necessary to study how to meet the reduction of GHGs and NH_3 while ensuring the nutritional needs of crops are fulfilled. Due to the limited availability of large machinery, drip and sprinkler irrigation are the primary methods of slurry application in China, as they are relatively low-cost. Studies from abroad primarily focus on reducing pollution in livestock and poultry farms in terms of environmental impact[13,14], with some studies indicating that pre-acidified slurry for field application can reduce NH_3 emission[15,16]. In contrast, domestic studies have placed greater emphasis on crop fields[17–19]. However, there are still insufficient field experiments and on-site experimental data, particularly concerning practices in China.

Therefore, this study investigated the impact of different ratios of pig slurry to mineral fertilizers, slurry application methods (drip and sprinkler irrigation) and the pre-acidified slurry measure on GHG and NH_3 emission from soil during maize production in the field. Given the similarity of farmland conditions to those in some other countries and the availability of suitable land for cultivation, this study selected Heilongjiang Province in northeastern China as a typical representative area. The findings provided technical support for reducing emission following slurry application while promoting the efficient use of slurry resources.

2 Materials and methods

2.1 Experimental site

The field experiment was conducted from May to August 2023 in an experimental field of Sihetun (46°25′ N, 126°29′ E) in Pingshan Town, Lanxi County, Suihua City, Heilongjiang Province, which experiences a cold temperate monsoon climate. The region has hot and rainy summers, with autumn rainfall accounting for about 16% of the annual precipitation. The soil type is black calcareous soil. The basic physical and chemical properties of the soil (0–20 cm deep) are presented in the Supplementary Materials (Table 1).

2.2 Slurry preparation and application methods

The slurry used in the experiment was sourced from pig manure processed at the Muyuan Breeding Farm in Pingshan Town, Lanxi County, Suihua City, Heilongjiang Province. Different ratios of mineral fertilizers and slurry were applied to the field in various treatment groups. The crop planted in the experimental field was maize. The basic physical and chemical properties of the pig slurry at basal fertilizer application and topdressing are presented in Table 2. Seven treatments were applied in the experiment, details are shown in Table 3.

Pig slurry is initially produced by collecting liquid pig manure from a slated floor, which is then pumped into a storage tank for solid-liquid separation. The solid fraction is used to produce organic fertilizer and the liquid portion is transferred to a covered anaerobic lagoon for fermentation. In northeastern China, the fermentation period lasts about 45 days. After fermentation, the pig slurry is moved to a storage tank until it is ready for field application. In the acidification slurry (AS) group, the pig slurry is pre-acidified before fertilizer application. The slurry is removed from the storage tank and acidified to about pH 6 using concentrated sulfuric acid.

Table 1 Basic physical and chemical properties of 0–20 cm soil layer in the Lanxi experimental field

pH	EC ($\mu s \cdot cm^{-1}$)	OM ($g \cdot kg^{-1}$)	TN ($g \cdot kg^{-1}$)	AHN ($mg \cdot kg^{-1}$)	AP ($mg \cdot kg^{-1}$)	AK ($mg \cdot kg^{-1}$)	K^+ ($mg \cdot kg^{-1}$)	Na^+ ($mg \cdot kg^{-1}$)	Cl^- ($mg \cdot kg^{-1}$)	TSC ($g \cdot kg^{-1}$)
8.2	169.8	40.6	2.02	157	5.9	193	4.2	14.17	67.02	0.7

Note: EC, electrical conductivity; OM, organic matter; TN, total nitrogen; AHN, alkali hydrolyzed nitrogen; AP, available phosphorus; AK, available kalium; TSC, total salt content.

Table 2 The basic physical and chemical properties of pig slurry at two different stages

The period of slurry application	pH	AN ($mg \cdot L^{-1}$)	TN ($mg \cdot L^{-1}$)	TP ($mg \cdot L^{-1}$)	K^+ ($mg \cdot L^{-1}$)	COD ($mg \cdot L^{-1}$)
Base fertilizer period	6.89	950.54	1182.86	83.50	697.86	12027.14
Topdressing period	6.90	1135.52	1316.43	168.49	888.93	12439.14

Note: AN, ammonia nitrogen; TP, total phosphorus; COD, chemical oxygen demand.

Table 3 Grouping based on different pH levels, fertilization ratios, and fertilization methods

Treatment	Slurry pH	Basal fertilizer amount	Topdressing amount	Fertilization method
NF (no fertilization)	/	/	/	sprinkler irrigation
RS (raw slurry replacement)	/	28.11 $m^3 \cdot ha^{-1}$ slurry	16.87 $m^3 \cdot ha^{-1}$ slurry	sprinkler irrigation
AS (acidified slurry)	6	28.11 $m^3 \cdot ha^{-1}$ slurry	16.87 $m^3 \cdot ha^{-1}$ slurry	sprinkler irrigation
RC50S (replacing 50% chemical fertilizer)	/	37.49 $kg \cdot ha^{-1}$ chemical fertilizer	22.49 $m^3 \cdot ha^{-1}$ slurry	sprinkler irrigation
RC50D (replacing 50% chemical fertilizer)	/	37.49 $kg \cdot ha^{-1}$ chemical fertilizer	22.49 $m^3 \cdot ha^{-1}$ slurry	drip irrigation
RC30 (replacing 30% chemical fertilizer)	/	52.47 $kg \cdot ha^{-1}$ chemical fertilizer	13.49 $m^3 \cdot ha^{-1}$ slurry	sprinkler irrigation
TF (traditional fertilization)	/	74.96 $kg \cdot ha^{-1}$ chemical fertilizer	/	/

Based on common fertilizer application methods used by local farmers in northern China, two distinct groups were established: sprinkler irrigation group (RC50S; replacing 50% mineral fertilizer) and drip irrigation group (RC50D; replacing 50% mineral fertilizer). The sprinkler system had a strip with five holes installed every 1.5 m, with each hole having a diameter of 25.4 mm. The drip irrigation system used a 16 mm drip tape, with a water emitter placed every 0.2 m. The row spacing for maize was 0.6 m, and the drip irrigation belts were laid between every two rows of maize, with one belt in each alternate space. Both the RC50S and RC50D groups received the same amount of fertilizer, with pig slurry replacing 50% of the mineral fertilizer. This 50% refers to replacing an equivalent nitrogen content from the mineral fertilizer by mass with pig slurry.

The fertilizer application methods and ratios were determined based on previous research, which identified key factors influencing gas emission following pig slurry application. These factors include pH[15, 20–22], the ratios of pig slurry to mineral fertilizer[23–25] and the fertilizer application methods[26–29]. Acidification is widely recognized as an effective method for reducing NH_3 emission. Additionally, different ratios of slurry to mineral fertilizer and application methods significantly impact both GHG and NH_3 emission.

2.3 Sampling procedures

In the experiment, the static chamber method was used to monitor GHG emission and the indophenol blue colorimetric method to measure NH_3 concentrations. The base was positioned at one third of the center line of the area. The base of the static dark box remained in the experimental field throughout the entire period. A rubber hammer was used to drive the base into the soil until it was fully sealed, preventing any air from entering the static chamber. NH_3 was absorbed using a sponge absorption through an NH_3 volatilization absorption device (thick white pipe in Fig. 1(c)). The equipment used for gas sampling includes a static dark chamber with a base (50 cm × 50 cm × 50 cm), an automatic gas extractor, a 100 mL sampling gas bag, a vacuum pump, an anemometer and a hygrometer.

The sampling time for GHGs was from 8 to 10 a.m. In the first week after fertilizer application, samples were collected daily, then every 7 days. The entire sampling period was from May to August. Before sampling, the air bag was evacuated, and the base of the static dark box was filled with water. The automatic gas extractor and air bag were connected in series. The air bag valve was opened, and the automatic gas extractor was switched on extract air. The automatic gas extractor was set to sample at 0, 10, 20 and 30 min. Each gas bag collected 100 mL of gas, with a total of 4 samples collected per group. After sampling, the air bag valve was tightened and gas detection was completed within 5 days.

The NH_3 volatilization collection device (Fig. 1(a,b)) is inserted into soil about 10 cm. A sponge infiltrated with glycerol phosphate solution (50 mL phosphoric acid and 40 mL glycerol in 1 L) was placed in a straight pipe where about 10 cm above the ground, while another sponge was placed in the bent pipe at the other end to isolate the air. Each treatment plot had three devices. The different fertilizer application methods had different fertilizer application times. Drip irrigation took longer than sprinkler irrigation. The only difference between the RC50S and RC50D groups was the fertilizer application method. Due to the different application time of the same amount of pig slurry to the field, the impact on NH_3 volatilization also differed. With a longer application time, the

Fig. 1 Experimental site and layout. (a) Conditions at the experimental site and the approximate conditions of the surrounding areas. (b) Spatial distribution of the seven treatment groups at the experimental site. There were 16 square plots in total, with nine of them designated for other experiments. (c) Silver cubic box in the picture was used for sampling GHGs, and the static dark box method was used to calculate the daily emission fluxes of GHGs. The white curved absorption tube was used for NH_3 absorption, and the sponge absorption method was used to calculate the daily emission fluxes of NH3. NF, no fertilizer; RS, raw slurry replacement; AS, acidified slurry; TF, traditional fertilization; RC30, replacing 30% mineral fertilizer; RC50S, replacing 50% mineral fertilizer (sprinkler irrigation); and RC50D, replacing 50% mineral fertilizer (drip irrigation).Test field in Sihetun in Pingshan Town, Lanxi County, Suihua City, Heilongjiang Province ((©Jiafeng Tong, (a,b) 14:00 P.M., May 6, 2023. (c) 15:00 P.M., July 15, 2023).

amount of NH_3 volatilization would be higher. NH_3 emission capture began on the day of fertilizer application. NH_3 collection devices were placed at different locations within each treatment plot, with samples taken the following morning at 7 a.m. During sampling, the sponge in the straight pipe was replaced and placed in numbered, sealed plastic bags. New sponges were used as replacements. The sponge at the bent end was replaced every 7 days. After replacing the sponge at the bent end, the next NH_3 capture cycle began, with devices repositioned accordingly. The sponges in the numbered, sealed plastic bags were transported back to the laboratory, immersed in 400 mL of 1 mol/L KCl solution, and shaken for 1 h. The ammonia nitrogen in the leachate was determined using the indophenol blue colorimetric method.

2.4 Calculation of GHG and NH_3 emission

2.4.1 GHG emission fluxes

The gas emission fluxes of GHGs are calculated as:

$$F = \rho \times \frac{V}{A} \times \frac{\mathrm{d}c}{\mathrm{d}t} \times \frac{273}{273+T} \tag{1}$$

where, F is the emission flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$), ρ is GHG density under standard conditions, the density is 0.714 $\mathrm{kg \cdot m^{-2}}$ for CH_4 and 1.96 $\mathrm{kg \cdot m^{-2}}$ for N_2O, respectively, V/A is the volume-to-area and the actual height of the box, A is the bottom area of the box, $\mathrm{d}c/\mathrm{d}t$ is the rate of change in gas concentration inside the box per unit time, which can be expressed by the slope K of the gas curve corresponding to the four sampling time points ($R^2 > 0.9$), and T is the temperature inside the box during sampling.

Due to the limitations of fertilizer application methods in the field under drip irrigation conditions, fertilizer application cannot cover the entire planting area as comprehensively as with sprinkler irrigation. Therefore, there are two approaches for calculating the emission flux in drip irrigation plots. One is the area method, because the drip irrigation belts are laid at intervals calculated as:

$$F_A = \frac{F + F_{TF}}{2} \tag{2}$$

where, A is the area of maize farm in $\mathrm{m^2}$, F is the emission flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$) and F_{TF} is the mineral fertilizer (TF) group emission flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$).

The other approach is the single-hole emission calculation method, where the flux is based on the number of drip irrigation holes per unit area that discharge:

$$F_H = \frac{F \times 10000}{0.5 \times 0.5 \times 2 \times 1.2 \times 0.2} \tag{3}$$

where, F_H is the single-hole emission calculation ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$), F is the emission flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$), 0.5 is the side length of the static box (m), 10000 is for conversion ($\mathrm{m^2} \rightarrow \mathrm{ha}$), 1.2 is the spacing between drip irrigation tapes (m), 0.2 is the distance between the two holes on belt (m).

2.4.2 Cumulative GHG emission

The cumulative emission of GHGs are calculated as:

$$Q = \Sigma_i^n \left(\frac{F_{i-1} + F_i}{2} \times 24 \times \frac{D_i}{1000} \right) \tag{4}$$

where, Q is the cumulative emission ($\mathrm{kg \cdot ha^{-1}}$); F_i is the emission flux of the i-th sampling, and D_i is the number of days between the (i–1)-th and i-th sampling.

2.4.3 The relevant calculations for NH_3 emission

The NH_4^+-N content is calculated using the following formula:

$$\mathrm{NH_4^+ - N_{content}} = \frac{m}{A} \times \frac{V_1}{V_2} \times \frac{ts}{D} \times 10^{-5} \tag{5}$$

where, m is the content of NH_4^+-N in the color-developing solution (μg), V_1 is the volume of the leachate (mL), ts is the sampling multiple; V_2 is the volume of the color-developing solution (mL); A is the cross-sectional area of the capture device ($\mathrm{m^2}$); and D is the duration of each consecutive capture (day).

2.5 Meteorological conditions

Meteorological conditions, including wind speed, humidity, temperature and precipitation, were monitored throughout the entire experimental period. Wind speed and humidity were measured at the time of air sampling. The anemometer used to measure wind speed was model YW-561M, and the hygrometer used for measuring humidity was model PM6252A. Precipitation was measured using a rain gauge.

2.6 Statistical analysis

A significant analysis of collected data was performed based on the student *t*-test by using Origin 2022 (OriginLab, Northampton, MA USA) and GraphPad Prism (v9.5.1, GraphPad Software, Boston, MA, USA). The threshold of statistical significance was set at $P < 0.05$.

3 Results and discussion

3.1 Daily NH_3 emission fluxes and cumulative NH_3 emission

NH_3 sampling was conducted in two phases, following basal fertilizer application and topdressing. After fertilizer application was completed, NH_3 was collected for about 20 days in each phase. NH_3 emission peak occurred in the first week following fertilizer application. As shown in Fig. 2(a), the raw slurry replacement (RS) group had the highest NH_3 emission rate of 4.93 $\mathrm{kg \cdot ha^{-1} \cdot d^{-1}}$ immediately after fertilizer application. Following basal fertilizer application (Fig. 2(a)), no significant differences in NH_3 emission rates were observed between the treatment groups ($P > 0.05$). Following topdressing (Fig. 2(b)), the initial RS group again had the highest NH_3 emission rate, reaching 4.20 $\mathrm{kg \cdot ha^{-1} \cdot d^{-1}}$. Despite this peak, no significant differences in NH_3 emission rates were

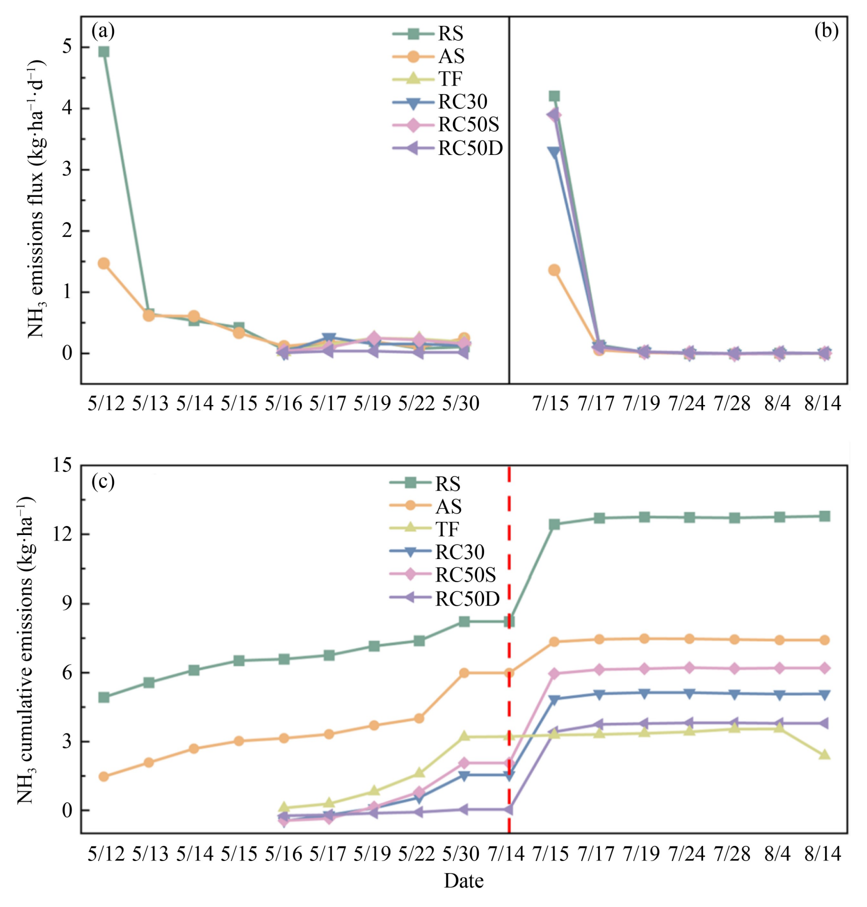


Fig. 2 (a) Daily NH_3 emission fluxes following basal fertilizer application. (b) Daily NH_3 emission fluxes following topdressing application. (c) Cumulative NH_3 emission. To left of the dashed vertical line is the cumulative NH_3 emission following basal fertilize application, and to the right is the cumulative NH_3 emission following topdressing, based on the emission from the basal fertilizer. Since NH_3 emission are concentrated in the week following fertilizer application, NH_3 monitoring after fertilizer application was only carried out for about 20 days in both stages. RS, raw slurry replacement; AS, acidified slurry; TF, traditional fertilization; RC30, replacing 30% mineral fertilizer; RC50S, replacing 50% mineral fertilizer (sprinkler irrigation); and RC50D, replacing 50% mineral fertilizer (drip irrigation).

observed between the treatment groups following topdressing ($P > 0.05$). These data indicate that NH_3 emission in soil were primarily concentrated in the few days immediately following fertilizer application.

As shown in Fig. 2(c), following basal fertilizer application, the RS group had the highest cumulative NH_3 emission, reaching 8.23 kg·ha^{-1}. The cumulative NH_3 emission following topdressing was added to the basal fertilizer emission, with the RS group again having the highest cumulative NH_3 emission flux, reaching 12.8 kg·ha^{-1}. The NH_3 volatilization from the RS group was significantly higher than that from the TF (traditional fertilization) group ($P < 0.01$). This was likely because organic nitrogen in the slurry underwent nitrification more readily than inorganic nitrogen from mineral fertilizers commonly used in traditional fertilization systems. Compared to the RS group, it was clear that acidification treatment significantly reduced NH_3 emission ($P < 0.01$). The total cumulative emission for the AS and RS groups were 7.4 and 12.8 kg·ha^{-1}, respectively. The AS group reduced NH_3 emission by 42.1% compared to the RS group. A previous study found that pre-acidification of pig slurry for field application reduced the emission of both GHGs and NH_3, which aligned with our experimental results[30]. Also, a study acidified five types of slurry, achieving a reduction of over 60% in NH_3 emission for all types except pig slurry, which showed little to no reduction[31]. However, in this experiment, pig slurry demonstrated a reduction in emission.

Replacing 30% of the mineral fertilizer with pig slurry for field application (RC30) resulted in the lowest cumulative NH_3 emission, at 5.08 $kg{\cdot}ha^{-1}$, a 60.4% reduction compared to full replacement (RS), with no significant impact on maize yield ($P > 0.05$). When comparing the RC50S and RC50D groups, significant differences in NH_3 emission were observed for both sprinkler irrigation and drip irrigation ($P < 0.05$). The total cumulative NH_3 emission for the RC50D(H) group was 3.79 $kg{\cdot}ha^{-1}$, while the RC50D(A) group had 3.56 $kg{\cdot}ha^{-1}$, compared to 6.20 $kg{\cdot}ha^{-1}$ for the RC50S group, respectively, where H and A denote the hole-based and area-based calculation methods. Drip irrigation reduced NH_3 emission by 38.9%–42.6% compared to sprinkler irrigation. Previous studies indicated that disc injection reduced average NH_3 emission by 38% compared to trailing shoe application [32].

3.2 GHG emission fluxes

The fluxes of methane emission differed from those of nitrous oxide, with CH_4 showing negative absorption (Fig. 3). This was likely due to factors such as soil moisture and pore structure, which caused CH_4 emission to exhibit a negative absorption state.

Following basal fertilizer application (Fig. 3(a)), only the RS and AS groups had slurry applied. Acidification during this period had no significant impact on N_2O emission ($P > 0.05$). However, when comparing the RS and TF groups following basal fertilizer application, a significant difference in N_2O emission was observed ($P < 0.05$). This demonstrates that

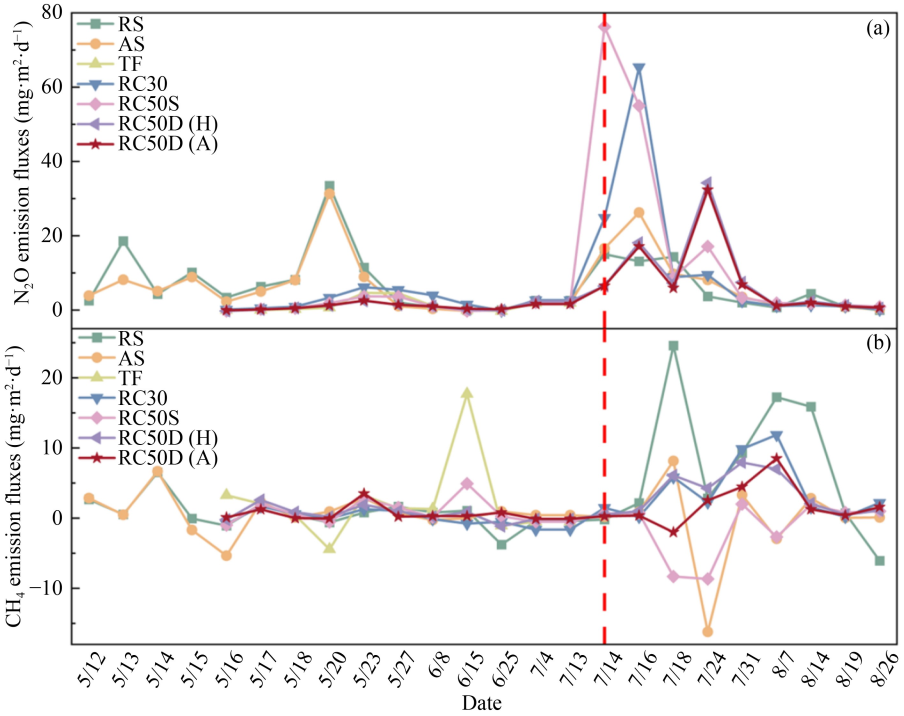


Fig. 3 Emission fluxes of N_2O (a), and CH_4 (b), following the field application of the treatment groups. From May 12 to July 13, to the left side of the dashed vertical line is the period following basal fertilizer application. From July 14 to August 26, to the right of the dashed vertical line is the period following topdressing fertilizer application. H is the accounting method for single-hole emission. A is the emission flux calculated using the area method. RS, raw slurry replacement; AS, acidified slurry; TF, traditional fertilization; RC30, replacing 30% mineral fertilizer; RC50S, replacing 50% mineral fertilizer (sprinkler irrigation); and RC50D, replacing 50% mineral fertilizer (drip irrigation).

replacing mineral fertilizer with slurry resulted in significantly higher N_2O emission. Following topdressing (Fig. 3(a)), no significant difference was found between the RS and AS groups ($P > 0.05$), indicating that acidification had no significant influence on N_2O emission. There was no significant difference between the RS, RC30 and RC50S groups ($P > 0.05$), indicating that there was no significant difference in N_2Oemission when only mineral fertilizers were applied. The RC50S and RC50D groups, however, demonstrated that the fertilizer application practice significantly impacted N_2O emission ($P < 0.05$). Drip irrigation was found to reduce nitrous oxide emission. Following topdressing, N_2O emission increased sharply. Following topdressing, slurry was used to replace mineral fertilizers in several groups. Since the slurry contains substantial amounts of organic nitrogen, this resulted in an increase in N_2O emission. Additionally, abundant precipitation and significant rainfall before and after topdressing led to a sudden variation in N_2O emission around the topdressing phase.

Following basal fertilizer application (Fig. 3(b)), no significant differences were observed between the RS and AS groups ($P > 0.05$), indicating that acidification had no significant influence on soil CH_4 emission. No significant variance was found between the RS and TF groups ($P > 0.05$), indicating that the application of slurry and mineral fertilizers had no notable impact on CH_4 emission. The RC30, RC50S and TF groups used varying amounts of mineral fertilizer at the basal fertilizer application stage (Fig. 3(b)), but no significant effect was detected between the groups ($P > 0.05$). This indicates that the amount of mineral fertilizer applied had no significant effect on soil CH_4 emission. Following topdressing, a significant difference was found between the RS and AS groups ($P < 0.05$), indicating that acidification significantly affected soil CH_4 emission at this stage. In contrast to the negligible difference in CH_4 emission following basal fertilizer application, it is likely that the growth stage of maize influenced gas emission. Both sprinkler irrigation and drip irrigation significantly impacted CH_4 emission ($P < 0.05$). The CH_4 emission measured with drip irrigation were higher than those with sprinkler irrigation, with the latter group having a negative absorption state following topdressing.

3.3 Cumulative GHG emission and GHG emission expressed in CO_2 equivalent

Following basal fertilizer application (Fig. 4(a)), no significant differences in cumulative soil N_2O emission were observed between the AS and RS groups ($P > 0.05$). However, a significant difference was found between the RS and TF groups ($P < 0.05$), indicating that slurry substitution for mineral fertilizers significantly increased N_2O emission. This increase may be attributed to the high organic nitrogen concentration in the slurry. Following topdressing (Fig. 4(a)), no significant difference in cumulative soil N_2O emission was found between the AS and RS groups ($P > 0.05$), indicating that acidification does not significantly affect N_2O emission. Additionally, no significant differences were observed between the RS, RC50S and RC30 groups ($P > 0.05$), indicating that the usage quantity of mineral fertilizers has no significant influence on the emission of N_2O.

From Fig. 4(a), it can be observed that the RC50S group had the highest cumulative N_2O emission, while the TF group had the lowest, at 5.12 and 0.90 $kg \cdot ha^{-1}$ respectively. The pre-acidification treatment reduced total N_2O emission by 2.1%. Malique also studied the impact of acidified slurry on N_2O emission in a mountain grassland system in southern Germany[33]. Overall, the differences between the acidified and non-acidified slurry treatments were not significant. The 30% and 50% substitution ratios increased total N_2O emission by 9.6% and 20.2%, respectively, compared to full slurry substitution. A study found that biogas slurry partially substituted for mineral fertilizer decreased the AOB-*amoA*, *nirK* and *nirS* copies by 28.4%–4.4%[34].

After topdressing, N_2O emission increased significantly. Drip irrigation in our study leads to a reduction by 12.4%–18.6% compared to sprinkler irrigation. The amount of pig slurry used during topdressing was noticeably higher than the basal fertilizer. The increase of pig slurry was positively correlated with N_2O emission. There was frequent heavy rainfall before and after the topdressing. Therefore, the sudden increase in N_2O emission was likely related to the rise in soil moisture. Also, at the jointing stage, plant roots released organic compounds, such as root exudates, as they grow. These organic compounds served as a carbon source for soil microbes, affecting their activity and altering the soil microbial community composition. Some root exudates could stimulate specific microbes, promoting nitrification and denitrification processes to increase N_2O emission[35–37].

Drip irrigation delivers water and fertilizer directly to the soil around the roots, potentially leading to elevate nitrogen concentrations in localized areas. In nitrogen-rich environments, soil microbes accelerated nitrification and

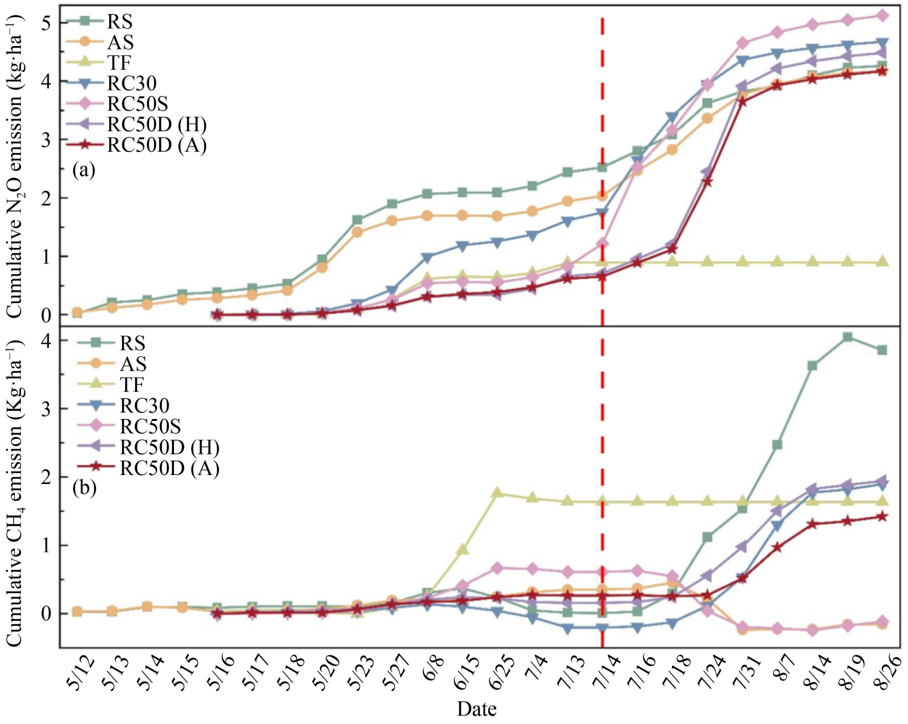


Fig. 4 Cumulative emission of N_2O (a) and CH_4 (b), following field application of the seven treatment groups. From May 12 to July 13 (1–64 days), to the left side of the dashed vertical line is the period following basal fertilizer application. From July 14 to August 26 (65–107 days), to the right of the dashed vertical line is the period following topdressing fertilizer application. RS, raw slurry replacement; AS, acidified slurry; TF, traditional fertilization; RC30, replacing 30% mineral fertilizer; RC50S, replacing 50% mineral fertilizer (sprinkler irrigation); and RC50D, replacing 50% mineral fertilizer (drip irrigation).

denitrification processes, potentially leading to increased N_2O emission[38]. Drip irrigation moistens only specific areas, creating alternating wet and dry cycles in the soil around the roots. Under moist conditions, microbial activity increases, promoting nitrogen transformation and producing N_2O[39]. Under dry conditions, nitrogen is less likely to be further denitrified into N_2O, reducing the amount of N_2O released into the atmosphere. Drip irrigation makes soil water distribution uneven and led to oxygen-deficient zones, promoting denitrification, which is a key pathway for N_2O production. In sprinkler irrigation, the water distribution is relatively even, ensuring sufficient soil oxygen, which helps to inhibit denitrification[40]. Drip irrigation systems require precise control of water volume. If irrigation frequency and amounts are insufficient, it may lead to low soil moisture, which can increase microbial nitrogen transformation and consequently raise N_2O emission.

Following basal fertilizer application (Fig. 4(b)), no significant difference was observed in the cumulative CH_4 emission from soil between the AS and RS groups ($P > 0.05$). However, a highly significant difference was found between the RS and TF groups ($P < 0.001$), indicating that the substitution of mineral fertilizer with slurry leads to a substantial increase in CH_4 emission. This phenomenon is likely attributable to the high organic carbon concentration in slurry. Additionally, significant differences in both the amount of mineral fertilizer applied and soil CH_4 emission were observed between the RC30, RC50S and TF groups ($P < 0.05$), indicating that inorganic nitrogen from mineral fertilizers also plays a role in influencing CH_4 emission. Following topdressing (Fig. 4(b)), a significant difference was observed between the RS and AS groups ($P < 0.001$), indicating that acidification has a remarkable influence on soil CH_4 emission. Acidification can markedly reduce CH_4 emission. Compared to the RS group, pre-acidified pig slurry effectively reduced CH_4 emission by

104%. The cumulative emission of the experimental group subjected to pre-acidification treatment (AS group) presented a state of negative absorption. In Fig. 4(b), it is evident that the RS group had the highest cumulative CH_4 emission, while the AS group had the lowest, at 3.85 and 0.15 kg·ha^{-1}, respectively. The RS group had significant discrepancies from the RC30 and RC50S groups ($P < 0.05$), indicating that the ratio of slurry substituting for mineral fertilizers has a pronounced influence on soil CH_4 emission. The RC50S group reduced CH_4emission by 103% compared to the full substitution group (RS). When comparing the RC50S and RC50D groups, it was clear that CH_4 emission of sprinkler irrigation for slurry application were lower than drip irrigation ($P < 0.05$). Sprinkler irrigation reduced CH_4 emission by about 107% compared to drip irrigation.

The equivalent emission of each GHG and the total GHG CO_2 emission equivalent for the Harbin Lanxi experimental farm during maize production from May to August 2023 are presented in the figure below (Fig. 5). In Fig. 5, it is clear that the TF group had the lowest total N_2O emission in CO_2 equivalents, while the highest was the RC50S group, at 267 and 1530 kg·ha^{-1} CO_2 eqv, respectively. The RC50D group had the lowest total CO_2 emission, while the RC50S group had the highest, at 4980 and 1650 kg·ha^{-1} CO_2 eqv, respectively. The AS group had the lowest total CH_4 emission in CO_2 equivalent, while the RS group had the highest, at 3.82 and 96.4 kg·ha^{-1} CO_2 eqv, respectively. The RC50D group had the lowest total GHG emission in CO_2 equivalent, while the RC50S group had the highest, at 3590 and 3170 kg·ha^{-1} CO_2 eqv, respectively. The total GHG emission of pure mineral fertilizers group was significantly lower than pig slurry, whether partial or complete substitute of mineral fertilizers in field applications.

However, under two calculation approaches, the emission range of drip irrigation is approximately at the level of that when only mineral fertilizers are used. This demonstrates that drip irrigation can exert a remarkable effect in reducing greenhouse gas emission. Among the groups combining the pig slurry and mineral fertilizers for field application, the RC30 group, which replaced 30% of mineral fertilizers with pig slurry, had the lowest total GHG emission, reducing by 96.4% compared to 50% substitution with pig slurry and 62.0% compared to fully submission group. The total GHG emission for the RC50S group was 3170 kg·ha^{-1} CO_2 eqv, whereas the RC50D(A) group was 713 kg·ha^{-1} CO_2 eqv and RC50D(H) group was 3590 kg·ha^{-1} CO_2 eqv. Drip irrigation leads to a reduction of total GHG emission by more than 9.1%–6.1% compared to sprinkler irrigation.

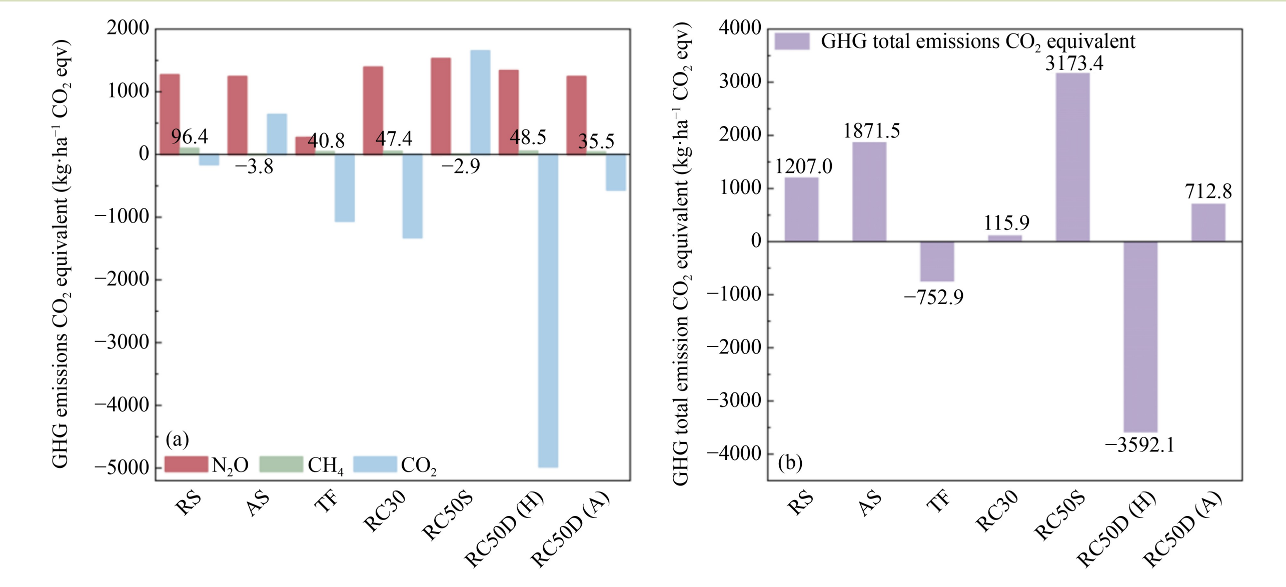


Fig. 5 (a) Cumulative emission of CH_4, N_2O and CO_2 in CO_2 equivalents. (b) Cumulative GHG emission in CO_2 equivalents. RS, raw slurry replacement; AS, acidified slurry; TF, traditional fertilization; RC30, replacing 30% mineral fertilizer; RC50S, replacing 50% mineral fertilizer (sprinkler irrigation); and RC50D, replacing 50% mineral fertilizer (drip irrigation).

3.4 Influence of meteorological factors

Since the experiment was conducted during spring and summer, the average daily temperature gradually increased over time, exceeding 20 °C (Fig. 6). Rising temperatures directly influenced GHG emission, particularly NH_3 emission ($P < 0.001$), with higher temperatures being associated with an increase in NH_3 emission. Wind speed had a significant effect on NH_3 ($P < 0.001$), CH_4 ($P < 0.001$), and N_2O ($P < 0.001$) emission. Relative humidity also significantly influenced NH_3 emission ($P < 0.001$) and GHG emission ($P < 0.001$) (Fig. 6).

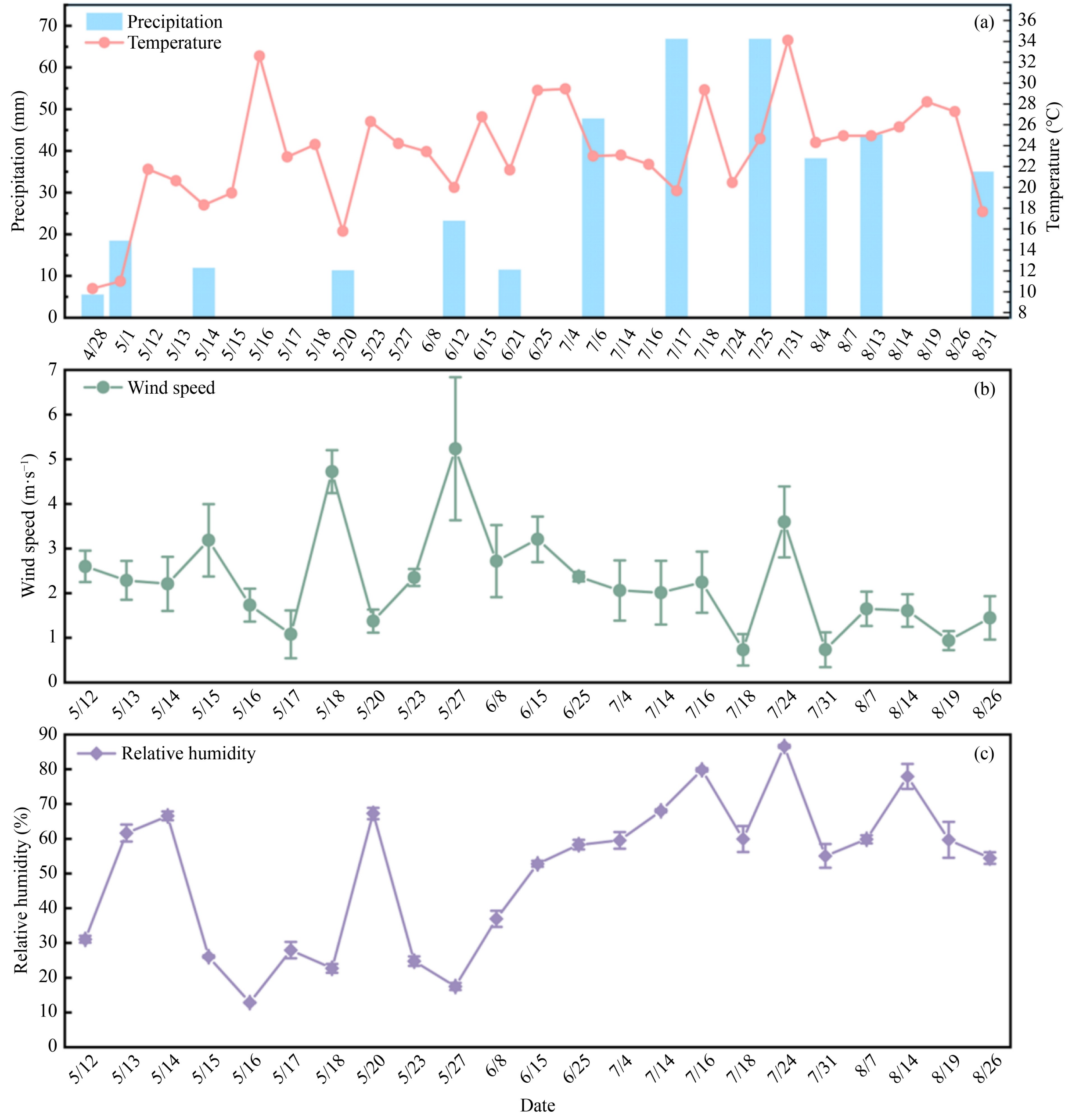


Fig. 6 Field temperature, precipitation (a), wind speed (b), and relative field humidity (c) following slurry application to the field.

The impact of temperature and precipitation (Fig. 6) on N_2O emission was highly significant ($P < 0.01$). N_2O emission significantly increased under both pre- and post-rainfall conditions, as well as during high-temperature weather ($P < 0.01$). Using SPSS software, a significant correlation between temperature and N_2O emission was found for the CT group ($r = -0.524$, $P < 0.05$) and the SCT group ($r = 0.535$, $P < 0.05$). This indicates that temperature had a significant negative correlation with N_2O emission when slurry was used as a complete substitute for mineral fertilizer. Precipitation also significantly influenced N_2O emission ($P < 0.01$). Correlation analysis indicated that N_2O emission from agricultural soils were significantly correlated with climatic factors such as temperature and precipitation[41,42]. Petersen et al.[43]used isotopes to investigate seasonally distinct sources of N_2O in acid organic soil and found that N_2O emission were strongly related to water table dynamics, individual rain events, slope position, and soil nitrogen availability. Their experiments, which included periods II and III characterized by repeated rainfall, showed increased N_2O emission after rainfall events, consistent with the results of our experiment. N_2O emissions were linked to soil water content, with precipitation altering soil oxygen levels and moisture content, while temperature fluctuations affected microbial activity and plant growth within the soil. Both factors significantly influenced N_2O emission during maize production. The temporal dynamics of N_2O direct emission rates were closely tied to increases in soil moisture[44,45].

During the snow-covered period, when the climate was dry and soil water content was low, N_2O production primarily resulted from nitrification. After rainfall, when soil water content was high, N_2O production was mainly attributed to denitrification. At medium soil water content, about half of the N_2O emission originated from nitrification, while the other half came from denitrification[46–48]. Some studies have shown that the interactions between core bacterial and archaeal members across different groups, as well as within-group interactions of core bacterial members, collectively contribute to N_2O emission and their temperature sensitivity[49]. By absorbing water through their roots, plants reduce soil moisture, which allows more oxygen to enter and improves soil aeration. In well-aerated conditions, nitrification becomes more active, while denitrification is suppressed, leading to lower N_2O production since denitrification typically generates more N_2O in low-oxygen environments.

3.5 Changes in soil properties

The basic physical and chemical properties of the soil at depths of 0–20 and 20–40 cm, after fertilizer application and maize planting, are presented for different experimental groups in Table 4. For treatments labeled RC50D, the lowercase letters “a” and “b” denote different soil depth layers, where “a” represents 20–40 cm and “b” represents 0–20 cm.

After fertilizer application in the different experimental groups, no significant changes were observed in soil pH ($P > 0.05$), total nitrogen ($P > 0.05$) or available humus nitrogen ($P > 0.05$). Soil NO_3-N and the C/N ratio were identified as the most influential soil properties affecting N_2O emission, as determined through random forest analysis [34]. Under varying fertilizer application conditions, soil electrical conductivity increased, with the AS group showing the highest increase at 47.8%. The conductivity of the NF group decreased by 8.2%. The AS group also had the highest sulfate concentration at 219 $mg \cdot kg^{-1}$, while the TF group had the lowest at 28.7 $mg \cdot kg^{-1}$. Additionally, the TF group had the lowest concentration of available phosphorus and potassium at 6.5 and 2.8 $mg \cdot kg^{-1}$, respectively. At soil depths of 0–20 cm and 20–40 cm, the available potassium concentration decreased, with the RC30 and TF groups showing the most significant reductions of 55.2% and 55.5%, respectively ($P < 0.05$). Sodium concentration also decreased notably, with the NF and TF groups showing reductions of 57.1% and 45.2%, respectively. The total salt concentration of the soil increased by 100%, with the RC30 group showing the highest increase. In contrast, the total salt concentration of the NF and TF groups decreased by 35.7% and 21.4%, respectively.

The AS group had the highest yield per unit area (Table 5) and the NF group the lowest. This indicates that different fertilizer application ratios and methods can reduce the loss of essential nutrients following fertilizer application, minimize post-fertilizer application GHG and NH_3 emission, and maintain crop yield.

3.6 Economic cost analysis of drip irrigation

3.6.1 Core irrigation system

Initial equipment investment accounted for 60%–80% of total cost. The unit price of drip irrigation pipe ranges from 0.3 to 2 $yuan \cdot m^{-1}$, depending on the material (e.g., PE pipe and built-

Table 4 Physical and chemical properties of soil layers after maize planting in experimental plots

Treatment	pH	EC (μs·cm^{-1})	TN (g·kg^{-1})	Sulfate (mg·kg^{-1})	AHN (mg·kg^{-1})	AP (mg·kg^{-1})	AK (mg·kg^{-1})	K^+ (mg·kg^{-1})	Na^+ (mg·kg^{-1})	Cl^- (mg·kg^{-1})	Total salt content (g·kg^{-1})
RC50Da	7.9	185.2	1.2	55.9	110.3	6.2	106.3	2.9	15.5	61.9	0.7
RC50Sa	8.1	215.2	1.5	84.0	110.3	3.9	118.7	2.6	25.0	61.1	0.8
RC30a	8.0	206.3	1.6	60.1	136.0	13.9	103.7	3.0	15.4	84.5	1.2
ASa	8.3	250.9	1.7	203.0	141.7	16.9	122.3	2.6	19.6	57.1	0.9
RSa	8.0	217.9	1.4	62.9	126.7	4.9	117.7	2.6	13.6	77.6	1.3
NFa	8.3	152.9	1.1	30.4	106.0	4.1	127.3	2.1	6.4	31.8	0.5
TFa	8.4	172.3	1.4	26.9	99.3	3.2	122.0	2.1	8.5	51.4	0.6
RC50Db	7.8	218.9	2.2	88.2	187.3	29.1	217.0	9.4	24.7	84.8	0.9
RC50Sb	7.7	268.3	2.1	84.9	176.3	14.3	178.3	6.2	26.1	81.5	1.0
RC30b	8.0	234.1	2.1	86.0	176.3	22.4	172.0	5.7	21.4	80.0	1.4
ASb	8.2	284.9	2.1	231.9	173.7	63.4	198.7	7.2	34.6	53.7	0.9
RSb	8.0	205.9	1.9	75.1	173.0	15.1	167.3	5.4	25.6	51.7	1.1
NFb	8.2	159.0	2.0	34.1	149.7	16.2	159.0	3.6	6.9	24.2	0.4
TFb	8.5	166.0	2.2	30.5	150.3	9.8	153.0	3.5	8.5	45.0	0.5

Table 5 The total yield and yield per hectare across different treatment groups

Treatment	Significance	Plot yield (kg per 80 m^2)	Yield (kg·ha^{-1})
NF	/	76.1	9512.5
RS	$P < 0.05$	91.5	11437.5
AS	$P < 0.05$	102.2	12775
TF	$P < 0.05$	93.5	11687.5
RC30	$P < 0.05$	98.1	12262.5
RC50S	$P < 0.05$	96.3	12037.5
RC50D	$P < 0.05$	94.6	11825

in drip tape) and specifications (e.g., flow rate and wall thickness). The application rate is 1200–2250 m·ha^{-1}, with a cost of 360–4500 yuan·ha^{-1}. Head hub includes water pumps, filters, fertilizing tanks and pressure gauges. A small system (covering up to 4 ha) costs 5000–10,000 yuan, while large systems (covering roughly 7–20 ha) can cost tens of thousands of yuan, distributed to about 1500–7500 yuan·ha^{-1}. Auxiliary pipe fittings include main pipes, branch pipes, valves, connectors, etc., cost about 750–3000 yuan·ha^{-1}.

3.6.2 Land and installation costs

If the land is not regular, additional costs of 750–2250 yuan·ha^{-1} will be required for modifications (such as ridge formation and channel repair). From 750 to 2250 yuan·ha^{-1} will be needed for labor, with costs potentially higher for complex terrains (such as mountainous areas or greenhouses).

3.6.3 Operational and maintenance costs

Energy consumption includes water pump electricity or fuel costs, depending on irrigation frequency and land size, 750–3000 yuan·ha^{-1}·yr^{-1}. Drip irrigation tape (with a lifespan of 1–3 years) needs to be replaced regularly, with an average annual cost of 450–1500 yuan·ha^{-1}; filter cartridges and other accessories have an annual cost of 300–750 yuan·ha^{-1}. Daily inspection, adjustments, and cleaning of blockages, with an average annual cost of 450–1500 yuan·ha^{-1} for labor costs.

4 Conclusions

In summary, using 30% slurry as a replacement for mineral fertilizers and acidification resulted in the lowest cumulative NH_3 emission, reducing emission by 60.4% compared to full slurry application. Replacing 30% of mineral fertilizers with pig slurry for field application led to the lowest total GHG emission. Climate conditions, particularly precipitation, were crucial factors influencing GHG and NH_3 emission, with precipitation significantly affecting N_2O emission. Wind speed and humidity also played significant roles in influencing GHG and NH_3 emission. The field application of acidified slurry increased soil total nitrogen content, which benefited crop yield and substantially reduced NH_3emission. The optimal fertilizer application strategy was to replace 30% of mineral fertilizers with pre-acidified slurry via drip irrigation. This approach effectively reduced both GHG and NH_3 emissions. Further targeted experiments are needed to compare and refine the choice between drip and sprinkler irrigation for field applications. It is also essential to select the most accessible and economical fertilizer application tools for local farmers.

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Compliance with ethics guidelines

Ying He, Jiafeng Tong, Li Rong, Denghui Meng, Chenhui Zhou, Haotian An, Zhiping Zhu, Xiaoshan Hu, Chuan Wang, Min Zhao, Tianyu Yu, and Dezhao Liu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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