Effects of tillage practices and biochar application rates on soil properties and greenhouse gas emissions in farmland

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Abstract: Long-term land use can change land properties and is accompanied by greenhouse gas emissions. As a new type of soil amendment, biochar has shown certain potential in improving soil properties and greenhouse gas reduction. In order to improve soil resilience and reduce greenhouse gas emissions, this study set up three different tillage methods (RS, RT, ST) and four biochar application rates of 0, 1, 2, and 3 t/hm^2. This study aimed to investigate the impact of various tillage methods and biochar application rates on soil hydrothermal conditions, total nitrogen, nitrate nitrogen, and greenhouse gases. The results showed that the application of biochar

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under the three tillage methods could improve the soil hydrothermal environment and increase the contents of total nitrogen, nitrate nitrogen and ammonium nitrogen, and the effect of ST was the most significant. Meanwhile, the application of biochar under the three tillage methods had a significant effect on the reduction of greenhouse gas emissions, with the application of 3 t/hm^2 biochar showing the best effect, and ST being the most significant. The combination weight-TOPSIS comprehensive evaluation method showed that the RS3 scheme was the optimal scheme for improving soil properties and reducing greenhouse gas emissions. The research results have certain significance for the study of soil resilience and emission reduction and provide a practical basis for the research of farmland soil and greenhouse gases.

Keywords： Farming methods; Biochar; Soil properties; Greenhouse gases; TOPSIS method

Nomenclature	
RS	Rotary tillage + Stubble removal and tillage
RT	Rotary tillage
ST	Stubble removal and tillage
MC	Moisture content
TM	Temperature
TN	Total nitrogen
NO_3^--N	Nitrate nitrogen
NH_4^+-N	Ammonium nitrogen
R_{CO2}	CO_2 emissions
R_{N2O}	N_2O emissions
R_{CH4}	CH_4 emissions
GWP	Global warming potential

1 Introduction

At present, the increasingly pronounced extreme climate change worldwide is undermining the stable balance of the natural ecosystem, and it also brings severe and pressing challenges to the survival foundation and long-term development of humanity [1]. As climate change intensifies, global warming has become a major public concern. Farmland, a significant source of greenhouse gas emissions, contributes 14% of total emissions from human activities. Of these, methane (CH_4) and nitrous oxide (N_2O) account for 52% and 84%, respectively, of human-caused CH_4 and N_2O emissions [2]. As one of the three major black soil regions globally, the cultivated land in the Northeast Black Soil Region constitutes about 1/7 of the country's total cultivated land, and its grain yield constantly accounts for 1/4 of the nation's total grain output. It is truly a "Granary of China" [3]. However, for a long time, due to unscientific farming practices, soil fertility in Northeast China's black soil region has been facing increasingly severe degradation. This manifests in a continuous decline in soil organic matter content, damaged soil structure, and reduced water and fertiliser retention capacity, which in turn leads to insufficient nutrient supply for crop growth, resulting in fluctuating or even declining yields [4]. This decline in soil fertility not only directly impacts local farmers' economic returns but also severely hinders the sustainable development of agriculture in Northeast China's black soil region, posing a potential threat to national food security. Therefore, amid the dual pressures of global climate change and regional agricultural development, exploring pathways to synergistically reduce greenhouse gas emissions while enhancing soil fertility has emerged as a core breakthrough for achieving high-yield, efficient, eco-friendly, and sustainable agricultural development in the region. This approach will not only effectively mitigate farmland's contribution to climate warming but also restore the ecological functions of black soil, ensure stable grain production capacity, and provide solid support for China's agricultural green transition and the achievement of its "dual carbon" goals.

In agricultural production practice, as a key measure to regulate soil ecology and greenhouse gas emissions, different tillage methods have drawn wide attention for their effectiveness in improving soil physical and chemical properties, optimising soil environment, and influencing greenhouse gas emissions, and the effects of different methods present complex diversity [5]. Tillage practices, by altering biochemical parameters like soil carbon and nitrogen availability and microbial activity, drive the variability of greenhouse gas emissions at the field scale, rather than soil physical properties [2]. Rotary tillage breaks up soil clods, making soil particles distribute more evenly, and it significantly improves soil aeration and water permeability [6]. Some studies have shown that CH_4 and N_2O emissions under rotary tillage are significantly higher than those under rotational tillage and ploughing. It is also noted that rotary tillage enhances soil permeability, boosting methanogen activity, while damaging soil structure and intensifying N_2O release [7]. Stubble tillage chops up crop residues and buries them in the soil, adding organic matter. As residues decompose gradually in the soil, soil organic matter content rises, soil aggregate structure is optimised, and soil water and fertiliser retention capacity is enhanced [8]. Some studies have compared the impacts of stubble removal and surface mulching on soil respiration and microbial communities. It shows that stubble removal significantly boosts soil CO_2 emissions, yet combining it with organic fertilisers can cut down N_2O emissions by adjusting microbial activity. It emphasises that stubble removal management should be combined with nutrient input to balance carbon sequestration and greenhouse gas emissions [9].

Biochar, as a novel soil amendment, demonstrates certain potential in improving soil properties and mitigating greenhouse gas emissions, compared with the effects of tillage practices on soil properties and greenhouse gas reduction [10]. Applying biocharcoal to soil increases soil porosity, reduces soil bulk density, and enhances its water-holding capacity [11]. Because biochar is rich in organic carbon and nutrients, it can increase the content of organic carbon and nutrients in soil. The application of biochar to soil will affect the physical and chemical properties of soil, thereby affecting the emission of greenhouse gases. Multiple studies have shown that under different environmental conditions, the effects of biochar on greenhouse gas emissions in soil are diverse, including both positive and negative effects. Cayuela et al. [12] found that biochar application could significantly reduce soil N_2O emissions by 30.92%, while increasing CO_2 emissions by 22.14%. It had no significant overall impact on CH_4 emissions. Its effects are regulated by multiple factors, including the physical and chemical properties of biochar and soil texture. Zhang et al. [13] conducted anaerobic culture experiments to further reveal the microscopic mechanism: biochar reduces the abundance of denitrifying bacteria by increasing soil pH, resulting in a 98.9% reduction in peak N_2O emissions, but at the same time, it increases CH_4 emissions by 60.5% due to the increase in dissolved organic carbon content, showing the bidirectional regulatory effect of biochar on different greenhouse gases. The positive impact of biochar application on soil CH_4 and CO_2 emissions may result from the enhancement of underground primary productivity and the inhibition of methane-oxidising bacteria in the soil, whereas the negative effect may be associated with the decrease in enzyme activity and the ratio of methanogens to methane-oxidising bacteria [14]. Ribas et al. [15] found that adding biochar in summer would promote the emission of CH_4 in soil. Zhou et al. [16] studied and found that adding high-temperature woody biochar in the composting system could reduce the cumulative emission of CH_4 by 93.1%. Zhang et al. [17] applied biochar to the soil and observed for five months and found that biochar reduced soil N_2O emission by 41.7%, and the emission reduction effect was still maintained in the long term.

TOPSIS analysis is a classic multi-attribute decision-making method used to rank alternatives and select the optimal one. It ranks alternatives by calculating their relative distances from the positive and negative ideal solutions. Its advantages include no requirement for data distribution assumptions and the ability to intuitively reflect the relative merits of alternatives, making it widely applied in fields such as environmental assessment and theatre management. TOPSIS can integrate multi-dimensional soil indicators (e.g., pH, organic matter, nutrient availability) to quantify the impact of different land uses or management practices on soil health. Li et al. [18] employed TOPSIS to quantify the synergistic effects of multiple indicators, providing a scientific basis for optimising irrigation strategies in greenhouse tomato cultivation. TOPSIS enables comprehensive evaluation of how different agricultural management practices, such as no-tillage, biochar application, and organic fertiliser substitution, influence greenhouse gas emissions and soil properties, thereby identifying optimal solutions. Zhang et al. [19] utilised TOPSIS to assess the impact of agricultural extension services on sustainable agriculture, with indicators including N_2O emission reduction rate, soil organic carbon increase, and crop yield. The results demonstrated that the integrated biochar and organic fertiliser management mode (BCF6 treatment) achieved the highest comprehensive score, reducing N_2O emissions by 41.7% and increasing soil organic carbon by 28%, which validates the effectiveness of TOPSIS in multi-objective optimisation. TOPSIS can integrate the effects of biochar on soil physical, chemical, and biological properties and greenhouse gas emissions and screen the optimal biochar type and application rate. Sun et al. [20] evaluated the comprehensive benefits of biochar application rates by integrating the following indicators using TOPSIS: soil organic carbon sequestration, N_2O emissions, CH_4 emissions, crop yield, and economic cost. The results showed that the biochar application rate of 15 t/ha achieved the highest comprehensive score, realising the synergistic optimisation of carbon sequestration, emission reduction, and economic benefits. This paper demonstrates that TOPSIS can be used to quantify the "environmental-economic" win-win threshold for biochar application. Liu et al. [21] employed principal component analysis to find that the combination of the minimum water irrigation with biochar and fertiliser led to the highest corn grain yield and water use efficiency rankings.

Among existing studies, research focusing on altering tillage practices or adjusting biochar application rates alone is relatively common, whereas studies investigating the combined effects of both tillage methods and biochar dosages remain scarce. Therefore, this research examines soil properties and greenhouse gas emissions to explore how biochar influences soil resilience and greenhouse gas release. It evaluates the performance of different biochar application rates under varying tillage practices, employs the combined weight-TOPSIS comprehensive evaluation method to compare the relative merits of each treatment, and identifies the optimal biochar dosage and tillage strategy. This study aims to provide a scientific basis and support for soil improvement and greenhouse gas mitigation efforts.

2 Materials and Methods

2.1 Research Area and Biochar

The experiment was conducted from May to October 2024 in Lindian County, Daqing City, Heilongjiang Province (46° 98' N, 124° 99' E) (Fig. 1). Situated in the western Songnen Plain, this area serves as a critical transitional zone between Northeast China's black soil region and the arid/semi-arid regions to the west, exhibiting both the soil fertility characteristics of black soil regions and the climatic stress features of semi-arid areas. The study area has a temperate continental monsoon climate, with hot, rainy summers and cold, dry winters. The average annual temperature is approximately 4°C, annual precipitation ranges from 400 to 500 mm, and the average annual frost-free period is relatively short at around 129 days. The soil in this region is black soil, an important soil type in the western part of Northeast China's black soil area. The biochar was purchased from Jilin Hongyuan Jialianhe Bioenergy Co., Ltd., using corn stover as raw material. It was produced through a high-temperature pyrolysis process consisting of four core stages: raw material pretreatment, continuous pyrolysis, flue gas purification, and cooling collection. It was produced via high-temperature pyrolysis at 500 ~ 600°C.

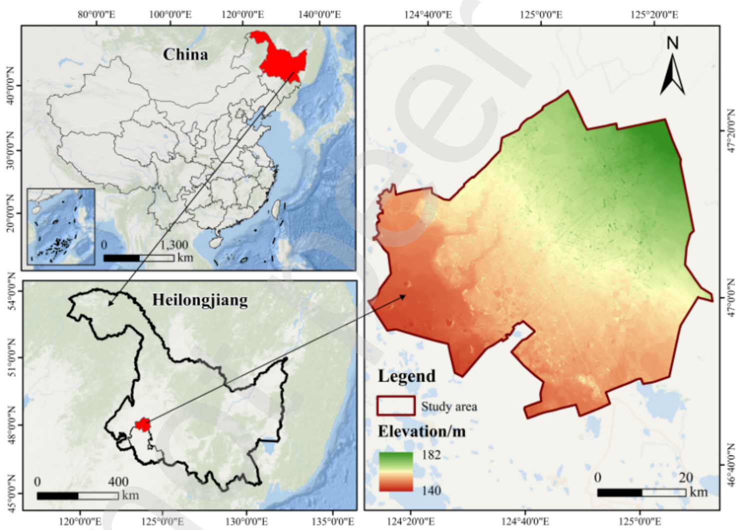

Fig.1 Survey of the study area

2.2 Design and Management of Experiments

Three tillage methods were employed in the experiment: rotary tillage combined with stubble breaking (RS), rotary tillage alone (RT), and stubble breaking alone (ST). Each tillage method was divided into 4 blocks according to a single-factor experimental design, with each plot measuring 6 m × 8 m. These 4 blocks received treatments of no biochar application (0 t/hm^2) and biochar applications at rates of 1, 2, and 3 t/hm^2, respectively. To prevent interference between different treatments, no samples were collected from the areas between adjacent blocks. Rotary tillage was performed using a rotary tiller, with the tillage depth controlled at 10 ~ 20 cm. Stubble management involves using a stubble crusher to shred residual root stubble and straw, incorporating them into the soil. The rotary tillage + stubble management method entails first performing stubble tillage, followed by rotary tillage. Before ploughing, biochar is manually broadcast onto the ridges in a single application, then thoroughly mixed into the 0-15 cm topsoil through tillage operations. After biochar-soil mixing is completed, the soil is left to settle for 7 days to allow full integration with biochar. Farmyard manure is used as the base fertiliser, with no additional fertilisers applied throughout the experiment. All other agronomic practices follow local conventional standards. The experimental design is shown in Fig. 2.

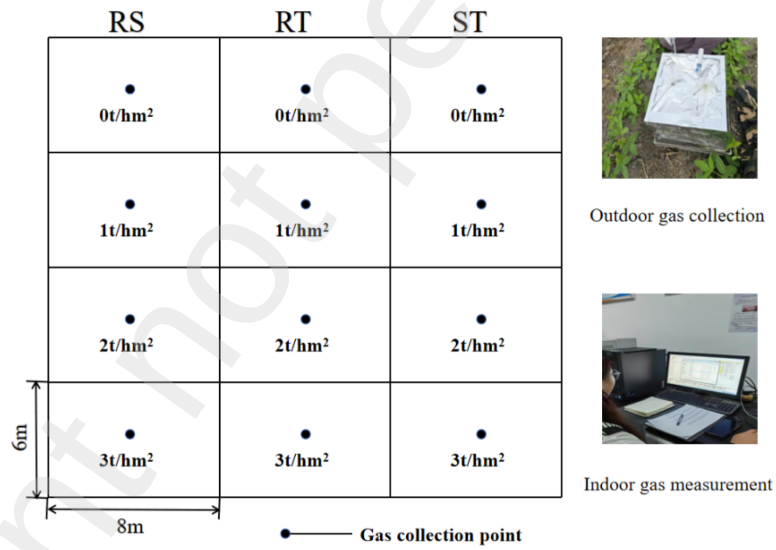

Fig.2 Experimental design diagram

2.3 Soil Sample Collection and Analysis

To investigate how different tillage practices and biochar affect soil physical and chemical properties, soil samples were collected from experimental plots under various treatments using the five-point sampling method for subsequent analysis of soil properties. Soil moisture content and temperature were measured with a WET-HH2 portable soil analyser (DELTA-T, UK). Total nitrogen content was determined via high-temperature digestion with concentrated sulphuric acid followed by analysis using an AA3 flow analyser. Inorganic nitrogen content was measured by extracting soil samples with 1 mol·L^{-1} KCl solution and subsequent analysis using an AA3 flow analyser.

2.4 Gas collection and measurement

Soil-emitted gases were collected using manual static chambers to analyse and calculate the emission fluxes of soil CO_2, CH_4, and N_2O. The static chamber for collecting gas samples consists of a square base with a water trough pre-installed 20 cm into the soil and a cuboid (40 cm × 40 cm) with one end closed. A thermometer and a gas sampling device are installed inside the closed cuboid, and the outside of the closed cuboid is wrapped with tin foil to prevent solar radiation from changing the temperature inside the chamber. During sampling, the closed cuboid is placed on the pre-embedded base, and water is added to the water trough for sealing. A closed cubic chamber was used to collect gas samples every 0, 10, 20, and 30 minutes with a suction pump. Before each sampling, the gas in the sampling line was purged, and the collected gas was stored in gas sampling bags while recording the internal temperature of the chamber. On June 15, June 28, July 11, July 22, August 3, August 13, August 25, September 5, September 22, and October 5, samples were taken. The concentrations of CO_2, CH_4, and N_2O gases were measured using a GC -2010 Plus gas chromatograph (Shimadzu Co., Japan). Then, the gas emission flux was calculated, and the global warming potential value (GWP) was computed. The calculation formula [22] is as follows:

$$F = \frac{dc}{dt} \times \frac{M}{V_0} \times \frac{P}{P_0} \times \frac{T_0}{T} \times H \quad (1)$$

Where F represents gas emission flux, with units of $mg \cdot m^{-2} \cdot h^{-1}$ or $\mu g \cdot m^{-2} \cdot h^{-1}$; dc/dt is the slope of the regression curve of gas concentration changing with time; M is the molar mass of gas, in $g \cdot mol^{-1}$; P is the local atmospheric pressure, in kPa; T is the actual temperature inside the static chamber, in K; V_0, P_0 and T_0 are the molar volume of gas under standard atmospheric pressure in $L \cdot mol^{-1}$, standard atmospheric pressure in kPa, and atmospheric temperature in K, respectively; H is the height of the static chamber, in m.

$$R = \sum (F_{i+1} + F_i)/2 \times (t_{i+1} - t_i) \times 24 \quad (2)$$

Where R is the cumulative emission of soil gas, in $kg \cdot hm^{-2}$; F_i is the gas emission flux at the i-th sampling, in $mg \cdot m^{-2} \cdot h^{-1}$ or $\mu g \cdot m^{-2} \cdot h^{-1}$; t_i is the sampling time at the i-th sampling, d.

$$GWP = R_{CO_2} + R_{CH_4} \times 25 + R_{N_2O} \times 298 \quad (3)$$

Where R_{CO_2}、R_{CH_4}、R_{N_2O} representse the emissions of CO_2, CH_4, and N_2O.

2.5 Combination Weight-TOPSIS Comprehensive Evaluation Method

In multi-criteria decision analysis, TOPSIS and Principal Component Analysis (PCA) are two classic evaluation methods that solve complex decision problems from different perspectives. TOPSIS conducts sequencing by computing the relative proximity of each alternative to the ideal solution and negative ideal solution, which intuitively reflects the advantages and disadvantages of alternatives and is suitable for scenes that require clear aspirational goals. PCA, on the other hand, fetches principal components of data through dimensionality reduction and determines metric weights by taking advantage of variance contribution rates, which effectively eliminates the interference of dependence among metrics and is suitable for processing high-dimensional data with info overlap. Combining the two methods to optimise the weighted matrix of TOPSIS with the objective weights generated by PCA can not only hold the sequencing intuitiveness of TOPSIS but also enhance the scientificity of weights through the statistical attributes of PCA, thereby constructing a more balanced and robust comprehensive evaluation system.

2.5.1 TOPSIS method

(1) To construct the original decision matrix, experimental data were collected for 8 metrics (CO_2, N_2O, CH_4, soil moisture content, temperature, total nitrogen, NH_4^+-N, NO_3^--N) across 12 tillage methods (RSCK, RS1, RS2, RS3, RTCK, RT1, RT2, RT3, STCK, ST1, ST2, ST3). These data formed the original decision matrix $X = (X_{ij})_{12\times8}$, with the 8 metrics categorised as follows: Positive metrics included CH_4, moisture, temperature, and total nitrogen, while negative metrics included CO_2, N_2O, NH_4^+-N, and NO_3^--N.

(2) Standardise the positive and negative indicators, respectively, to achieve a unified order of magnitude and evaluation scale:

$$Y_{ij} = \frac{(X_{ij} - X_{min})}{(X_{max} - X_{min})} \quad (4)$$

$$Y_{ij} = \frac{(X_{max} - X_{ij})}{(X_{max} - X_{min})} \quad (5)$$

Where X_{ij} denotes the contribution of the i-th tillage practice to the j-th evaluation index.

(3) Calculation of index entropy value by entropy weight method:

$$P_{ij} = Y_{ij}/\sqrt{\sum_{j=1}^{n} Y_{ij}^2} \quad (6)$$

If $\sum_{j=1}^{n} Y_{ij}=0$, then $P_{ij}=0$

$$e_{ij} = -\frac{1}{ln12} * \sum_{j=1}^{12}(P_{ij} * ln(P_{ij})) \quad (7)$$

If $P_{ij}=0$, definition $P_{ij} * ln(P_{ij})=0$

Calculate weight: $w_j^{'} = (1 - e_j)/\sum_{j=1}^{8} e_j$, the smaller the entropy, the greater the dispersion of the indicator, and the higher the weight.

2.5.2 Principal Component Analysis(PCA)

(1) Standardize the original indicators X_{ij}:

$$\overline{\mathrm{X}_{\mathrm{ij}}} = \frac{\mathrm{X_{ij}} - \mu_{\mathrm{j}}}{\sigma_j} \tag{8}$$

Where $\mu_j = \frac{1}{12}\sum_{i=1}^{12} \mathrm{X_{ij}}$ (average value of the j-th indicator), $\sigma_j = \sqrt{\frac{1}{11}\sum_{i=1}^{12} (\mathrm{X_{ij}} - \mu_{\mathrm{j}})^2}$ (standard deviation of the j-th index).

(2) Principal Component Analysis

Compute the covariance matrix, $\sum = \frac{1}{12}\overline{X}^T\overline{X}$, solving eigenvalue$\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_8$ and feature vectorsα_1, α_2, ... , α_8. Select the first k principal components (e.g., the first 3) where the cumulative variance contribution rate is ≥ 85%, and record the variance contribution rate of the m-th principal component as:

$$\eta_m = \frac{\lambda_m}{\sum_{m=1}^{8} \lambda_m} \tag{9}$$

(3) Calculating Principal Component Analysis Weights:

$$w_j^{PCA} = \frac{\sum_{m=1}^{k} |\alpha_{jm}| \cdot \eta_m}{\sum_{j=1}^{8}\sum_{m=1}^{k} |\alpha_{jm}| \cdot \eta_m} \tag{10}$$

Where α_{jm} is the loading (eigenvector element) of the j-th index on the m-th principal component. The larger the absolute value, the greater the contribution of the index to the principal component.

(4) Calculate the combined weights, with the entropy weight method weight as the main one (accounting for 60%) and the principal component analysis as the auxiliary one (accounting for 40%).

$$w_j = 0.6 \times w_j^{熵} + 0.4 \times w_j^{PCA}$$

(5) Constructing a weighted normalized matrix.

(6) Apply weights w_j to the normalized matrix:

$$R_{ij} = w_j * r_{ij} \tag{11}$$

Where r_{ij} is the standardized index value.

Determine the positive ideal solution A^+ and the negative ideal solution A^-:

$$A^+ = max(R_{i1}R_{i2}...R_{in}) \tag{12}$$

$$A^- = min(R_{i1}R_{i2}...R_{in}) \tag{13}$$

(7) Calculate the distances between each evaluation object and the optimal solution D_i^+ as well as the worst solution D_i^-. The formula for calculation is as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} Z_j(A_{ij} - A_j^+)^2} \tag{14}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} Z_j(R_{ij} - R_j^-)^2} \tag{15}$$

(8) Calculate the relative proximity and sort the relative proximity C_i to characterize the quality of the scheme:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{16}$$

Where $0 \leq C_i \leq 1$, the greater the value of C_i, the better the overall performance of the farming method.

2.6 Data analysis

In this study, experimental data were recorded using Excel 2019, with each dataset summarised by calculating the mean and standard deviation (S.D.). Data analysis was performed using SPSS 26: one-way analysis of variance (ANOVA) was employed to test for differences between treatments, followed by the least significant difference (LSD) method to determine significance, with the significance level set at 0.05. Pearson correlation coefficients were used for correlation analysis. Finally, graphs were generated using Origin 2022, and a combined weight-TOPSIS comprehensive analysis was applied to evaluate each treatment.

3 Result

3.1 Impact of Tillage Methods and Biochar Application Rates on Soil Water and Heat Environment

3.1.1 Effects of Tillage Methods and Biochar Application Rates on Soil Moisture Content

The effects of different tillage methods and biochar application rates on soil moisture content (MC) are shown in Fig. 3. Under RS tillage, biochar application significantly increased soil moisture content by 4.62 ~ 14.25% compared to the CK treatment. Under RT tillage, biochar application significantly increased soil moisture content by 15.39 ~ 37.06% compared to the CK treatment. Under ST tillage, biochar application significantly increased soil moisture content by 14.74 ~ 36.61% compared to the CK treatment. Overall, soil moisture content under all three tillage methods exhibited a trend of initial increase followed by decrease, with average values ranging from 27.816 to 31.989 mm across treatments. The 3 t/hm^2 biochar application maintained the highest soil moisture content throughout the experiment. With the same biochar application rate, ST tillage resulted in higher average soil moisture content than RS and RT tillage, because ST causes less soil disturbance than rotary tillage, thereby reducing water evaporation.

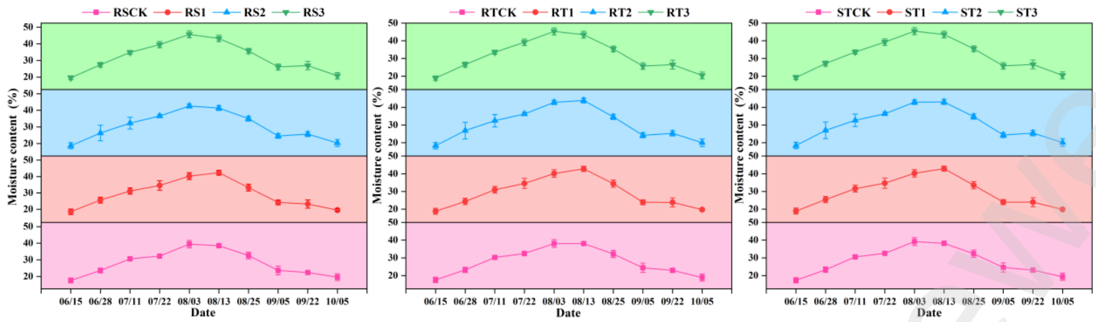

Fig. 3 Trends in soil moisture content under different treatments

3.1.2 Effects of Tillage Methods and Biochar Application Rates on Soil Temperature

The effects of different tillage methods and biochar application rates on soil temperature (TM) are shown in Fig. 4. Overall, soil temperature exhibited similar variation trends across the three tillage treatments, all characterised by gentle fluctuations. During the experiment, as solar radiation intensified, atmospheric temperatures rose, leading to a corresponding increasing trend in soil temperature. After August, soil temperatures gradually declined. Under RS tillage, biochar application significantly increased soil temperature by 2.34 ~ 10.37% compared to the CK treatment; under RT tillage, biochar application resulted in a significant temperature increase of 5.23 ~ 17.7% relative to CK; and under ST tillage, biochar application produced a significant 3.22 ~ 11.95% temperature rise compared with CK. The maximum temperature across all treatments ranged from 19.23 to 21.9℃, the minimum temperature from 9.02 to 11.98℃, and the average temperature from 19.40 to 91.87℃. With the same biochar application rate, ST exhibited a higher average soil temperature than SR and RT. This is because ST causes less disruption to soil structure, resulting in better-developed soil structure and superior thermal insulation.

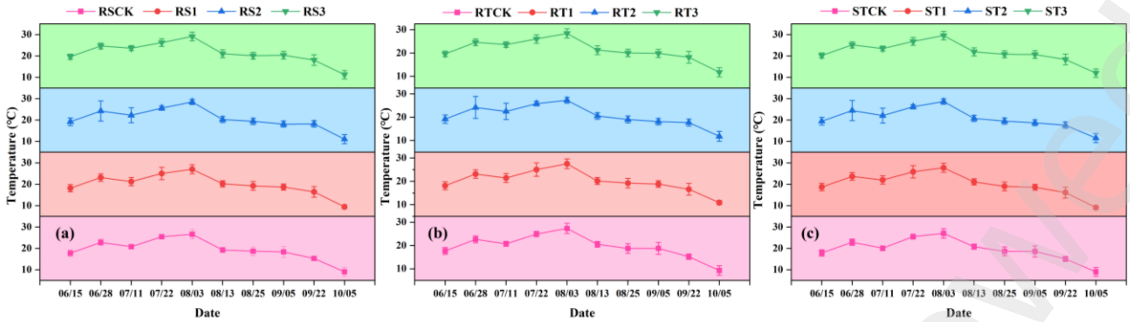

Fig. 4 Trends in soil temperature changes under different treatments

3.2 Effects of Tillage Methods and Biochar Application Rates on Soil Nutrients

3.2.1 Effects of Tillage Methods and Biochar Application Rates on Soil Total Nitrogen

The effects of different tillage methods and biochar application rates on soil total nitrogen (TN) are shown in Fig. 5. Under RS tillage, the order of TN content was RS3 ＞RS2 ＞RS1 ＞ RSCK. Compared with the CK treatment, biochar treatments significantly increased TN content by 15.68 ~ 67.73%. Under RT tillage, the order of TN content was RT3 ＞RT2 ＞RT1 ＞RTCK. Compared with the CK treatment, biochar treatments significantly increased TN content by 14.74 ~ 63.21%. Under ST tillage, the order of TN content was ST3 ＞ST2 ＞ST1 ＞STCK. Compared with the CK treatment, biochar treatments significantly increased TN content by 15.67 ~ 67.74%. These results indicate that biochar application effectively adsorbs soil nitrogen. At the same biochar application rate, ST tillage resulted in higher TN content than RS and RT tillage, thereby reducing nutrient leaching.

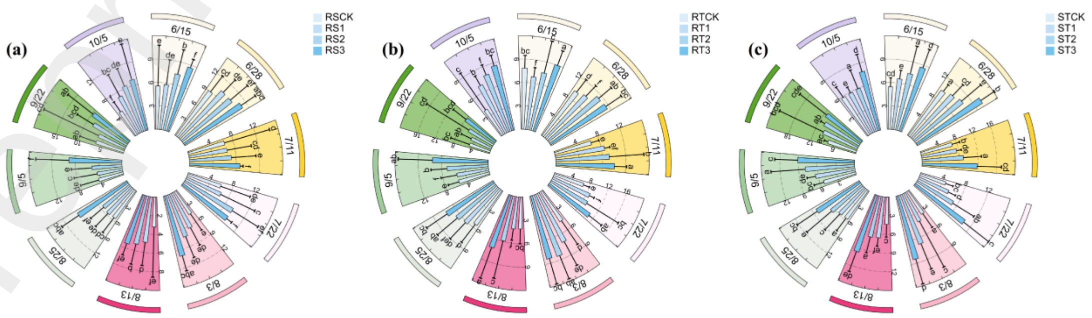

Fig. 5 Changes in soil total nitrogen under different treatments

3.2.2 Effects of Tillage Methods and Biochar Application Rates on Soil Nitrate Nitrogen

The effects of different tillage methods and biochar application rates on soil nitrate nitrogen (NO_3^--N) are shown in Fig. 6. Under the RS tillage method, compared with the CK treatment, biochar treatments significantly increased nitrate nitrogen content by 18.99 ~ 73.77%, with the order of nitrate nitrogen content being RS3 ＞RS2 ＞RS1 ＞RSCK. Under the RT tillage method, biochar treatments significantly increased nitrate nitrogen content by 29.98 ~ 106.72% compared to the CK treatment, following the order RT3 ＞RT2 ＞RT1 ＞RTCK. For the ST tillage method, the nitrate nitrogen content followed the sequence ST3 ＞ST 2＞ST1 ＞STCK, with biochar treatments significantly increasing nitrate nitrogen content by 30.70~100.63% relative to the CK treatment. These results indicate that biochar application effectively adsorbs soil nitrogen. At the same biochar application rate, ST tillage resulted in higher nitrate nitrogen content than RS and RT tillage, thereby increasing nitrate nitrogen levels.

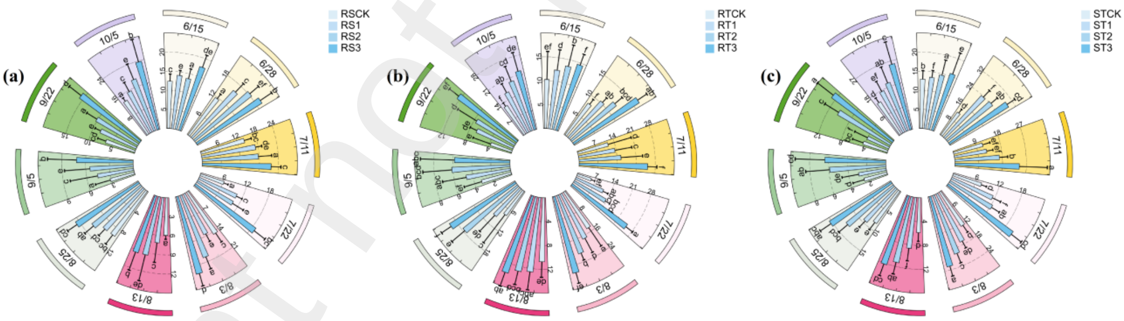

Fig. 6 Changes in soil nitrate nitrogen under different treatments

3.2.3 Effects of Tillage Methods and Biochar Application Rates on Soil Ammonium Nitrogen

The effects of different tillage methods and biochar application rates on soil ammonium nitrogen (NH_4^+-N) are shown in Fig. 7. Under the RS tillage method, compared with the CK treatment, biochar treatments significantly increased ammonium nitrogen content by 18.99 ~ 73.77%, with the order of RS3 ＞RS2 ＞RS1 ＞RSCK. Under the RT tillage method, biochar treatments significantly increased ammonium nitrogen content by 29.98 ~ 106.72% compared to the CK treatment, following the order of RT3 ＞RT2 ＞RT1 ＞RTCK. Under the ST tillage method, the ammonium nitrogen content exhibited the order of ST3 ＞ST2 ＞ST1 ＞STCK, with biochar treatments significantly increasing content by 30.70 ~ 100.63% compared to the CK treatment. These results indicate that biochar application effectively adsorbs soil nitrogen. At the same biochar application rate, ST tillage resulted in higher nitrate nitrogen content than RS and RT tillage, thereby increasing ammonium nitrogen levels.

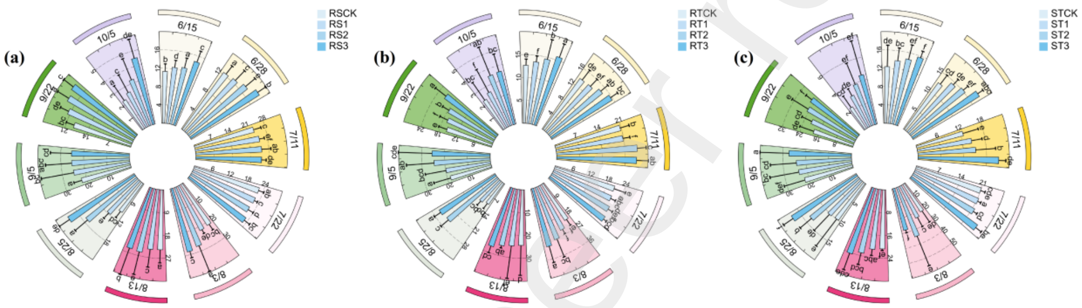

Fig. 7 Changes in soil ammonium nitrogen under different treatments

3.3 Effects of Tillage Methods and Biochar Application Rates on Greenhouse Gas Emissions

3.3.1 Effects of Tillage Methods and Biochar Application Rates on CO_2 Emissions

As shown in Fig. 8, the CO_2 emission flux of each treatment exhibited a unimodal temporal pattern, with emissions concentrated primarily between July 22 and August 25. During the early gas collection period, CO_2 emissions remained low and relatively stable across all treatments due to low soil temperatures and weak microbial activity. As soil temperatures subsequently increased, microbial respiration intensified, leading to a gradual rise in CO_2 emission flux that peaked on August 3. According to Fig. 11, under the three tillage methods, CO_2 emissions showed positive correlations with soil moisture, temperature, total nitrogen, nitrate nitrogen, and ammonium nitrogen, though the correlation strengths varied.

It can be seen from Table 1 that compared with R_{CO2} treated with RSCK, R_{CO2} treated with RS1, RS2 and RS3 increased by 2.80%, 6.5%, and 12.73%, respectively; compared with R_{CO2} treated with RTCK, R_{CO2} treated with RT1, RT2 and RT3 increased by 3.20%, 6.91%, and 11.28%, respectively; compared with R_{CO2} treated with STCK, R_{CO2} treated with ST1, ST2 and ST3 increased by 4.74%, 8.84%, and 12.74%, respectively. In conclusion, the application of charcoal can lead to an increase in CO_2 emission flux to a certain extent. Under the treatment of charcoal application rates, for CO_2 emission flux, RS ＞RT ＞ST.

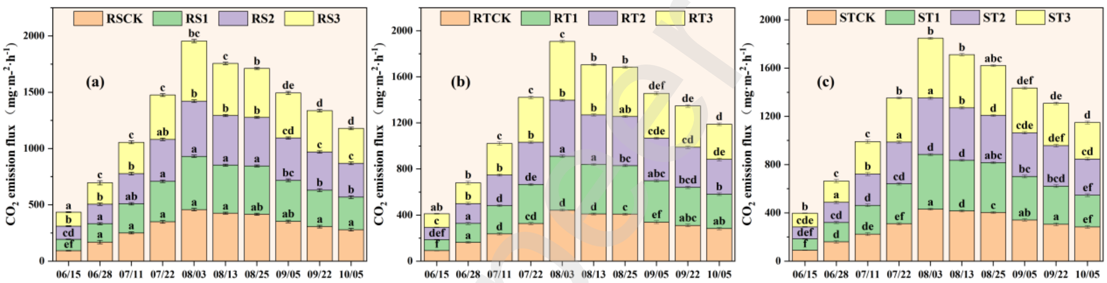

Fig. 8 CO_2 emission flux under different treatments

3.3.2 Effects of Tillage Methods and Biochar Application Rates on N_2O Emissions

As shown in Fig. 9, the N_2O emission fluxes of all treatments exhibited a decreasing trend over time. Emissions were primarily concentrated between July 22 and August 25. Starting from June 15, the N_2O emission flux fluctuated upward, peaking on August 3, after which it declined and subsequently stabilised. As indicated in Fig. 11, N_2O emission fluxes under different tillage practices all showed negative correlations. Across the three tillage methods, N_2O emissions were negatively correlated with moisture, temperature, total nitrogen, nitrate nitrogen, and ammonium nitrogen, though the correlation strengths varied.

As can be seen from Table 1, compared with the RSCK treatment, the R_{N2O} of the RS1, RS2, and RS3 treatments decreased by 9.80%, 25.86%, and 32.17% respectively; compared with the RTCK treatment, the R_{N2O} of the RT1, RT2, and RT3 treatments decreased by 7.70%, 22.82%, and 34.30% respectively. Compared with the STCK treatment, the R_{N2O} of the ST1, ST2, and ST3 treatments decreased by 9.72%, 23.12%, and 36.42% respectively; in conclusion, the application of biochar can significantly reduce N_2O emissions to a certain extent. Under the biochar application rate treatments, for N_2O emission flux, ST ＞RT ＞RS.

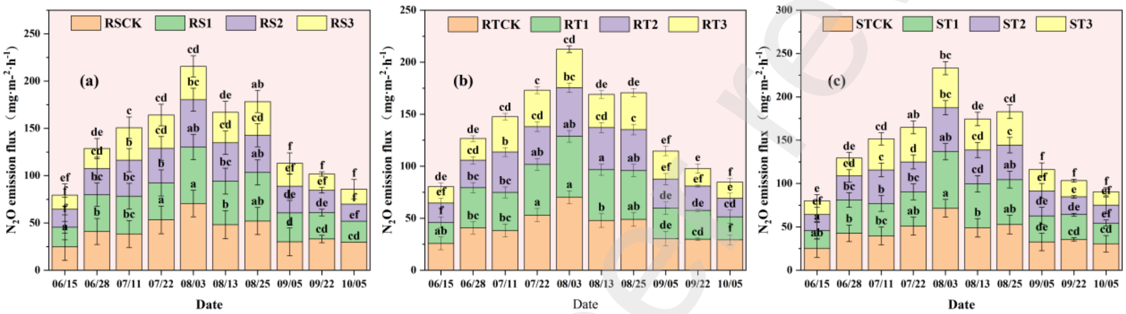

Fig. 9 N_2O emission flux under different treatments

3.3.3 Effects of Tillage Methods and Biochar Application Rates on CH_4 Emissions

Fig. 10 shows the trends of CH_4 emission fluxes for each treatment throughout the experimental period, where positive and negative values represent CH_4 emissions from and uptake by the soil to the atmosphere, respectively. As indicated in the figure, CH_4 was emitted between June 15 and June 22, and between September 5 and October 5, while CH_4 was absorbed from July 11 to September 5. According to the correlation analysis in Fig. 11, CH_4 emission flux was positively correlated with N_2O emissions and negatively correlated with all other factors.

As can be seen from Table 1, compared with the RSCK treatment, the R_{CH4} of the RS1, RS2 and RS3 treatments decreased by 123.17%, 214.318%, and 311.12%, respectively; compared with the RTCK treatment, the R_{CH4} of the RT1, RT2, and RT3 treatments decreased by 93.56%, 190.39%, and 274.56%, respectively. Compared with the STCK treatment, the R_{CH4} of the ST1, ST2, and ST3 treatments decreased by 105.00%, 190.39%, and 274.56%, respectively; in conclusion, the application of biochar can significantly reduce CH_4 emissions to a certain extent. For CH_4 emission flux, RS ＞RT ＞ST.

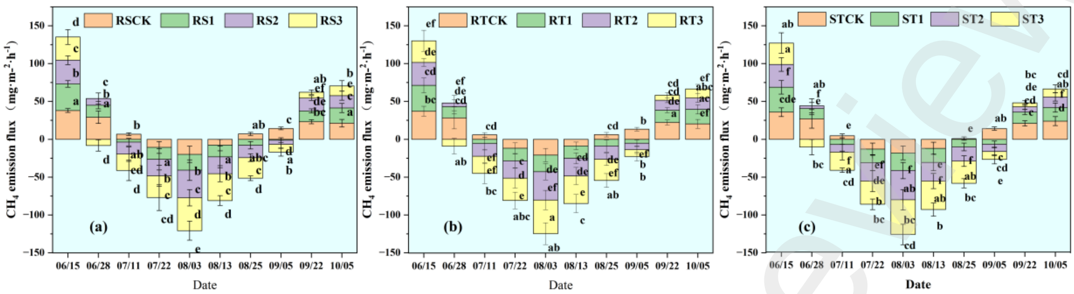

Fig. 10 CH_4 emission flux under different treatments

3.3.4 Correlation analysis

This study employed Pearson's bivariate correlation analysis to conduct an in-depth quantitative assessment of the correlations among soil hydrothermal conditions (MC, TM), soil nutrients (TN, NH_4^+-N, NO_3^--N), and greenhouse gases (R_{CO2}, R_{N2O}, R_{CH4}, GWP). The results are presented in Fig. 11. Overall, under the three tillage practices (RS, RT, ST), significant correlations were observed between soil hydrothermal factors, soil nutrient factors, and greenhouse gases; however, NO_3^-N under RS tillage showed no correlation with other factors. Specifically, across different tillage methods, soil hydrothermal factors (MC, TM) exhibited a significant (P <0.05) positive correlation with soil nutrient factors (TN, NH_4^+-N, NO_3^--N) and greenhouse gas (R_{CO2}), while demonstrating a significant (P <0.05) negative correlation with greenhouse gases (R_{N2O}, R_{CH4}, GWP). This indicates that the concurrent improvement of soil hydrothermal conditions enhances nutrient availability and CO_2 emissions while suppressing N_2O, CH_4, and GWP. However, due to its unique nitrogen cycling mechanism, the RS tillage method decouples NO_3^--N from this coupled system.

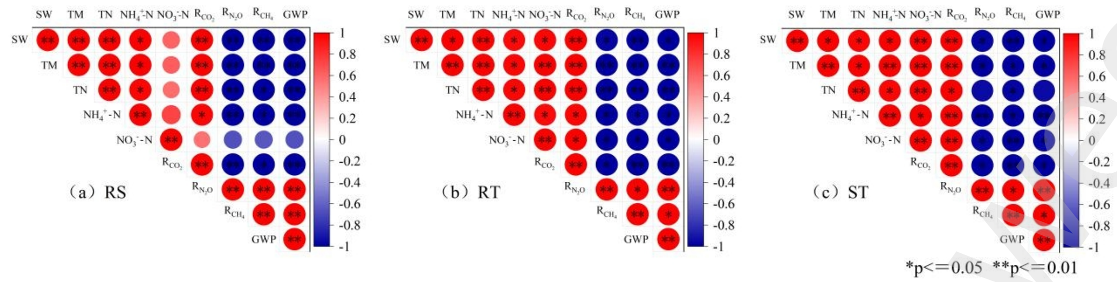

Fig. 11 Correlation analysis of CO_2, N_2O and CH_4 emission fluxes with soil moisture content, temperature, total nitrogen, nitrate nitrogen, ammonium nitrogen, and GWP under different treatments

Table 1 GWP and cumulative emissions of CO_2, CH_4, N_2O under different treatments

Treatments	R_{CO_2} (kg·ha^{-1})	R_{N_2O} (kg·ha^{-1})	R_{CH_4} (kg·ha^{-1})	GWP (kg CO_2-eq ha^{-1})
RSCK	5816.86±322.87bc	798.39±0.04ab	140.85±0.02a	247423.26±332.18bc
RS1	5979.93±223.61de	720.66±0.07a	-32.64±0.04ab	219921.71±242.39de
RS2	6195.89±262.87cd	161.01±0.04ab	-161.02±0.05ab	178681.55±268.98bc
RS3	6557.47±489.69a	541.96±0.04ab	-297.38±0.02c	160626.61±495.57a
STCK	5643.50±336.69bc	779.92±0.17ab	157.86±0.02ab	242006.94±354.57bc
ST1	5911.19±278.68ef	704.07±0.14ab	-7.89.±0.03ab	215526.66±291.93ef
ST2	6142.69±250.33de	599.62±0.13bc	-142.69±0.03bc	181263.08±267.05de
ST3	6362.82±392.53a	495.86±0.09d	-275.54±0.02c	147329.01±401.91a
RTCK	5556.60±284.25cd	764.75±0.04ab	175.82±0.02ab	237840.10±293.61bc
RT1	5734.36±213.46f	705.80±0.05ab	11.32±0.03ab	216346.78±226.84f
RT2	5910.81±256.18de	590.224±0.04bc	-106.21±0.02bc	179172.16±265.74de
RT3	6183.40±376.33ab	502.42±0.05cd	-206.9941±0.04c	149380.21±389.73ab

3.3.5 Analysis of Results from Group Weight - TOPSIS Comprehensive Evaluation Method

Comprehensively evaluate three different tillage methods, soil properties, and greenhouse gases according to the combination weight - TOPSIS comprehensive evaluation method. The larger the C_i is, the better the comprehensive performance of the tillage method is. The results are shown in Fig. 12 and Table 2.

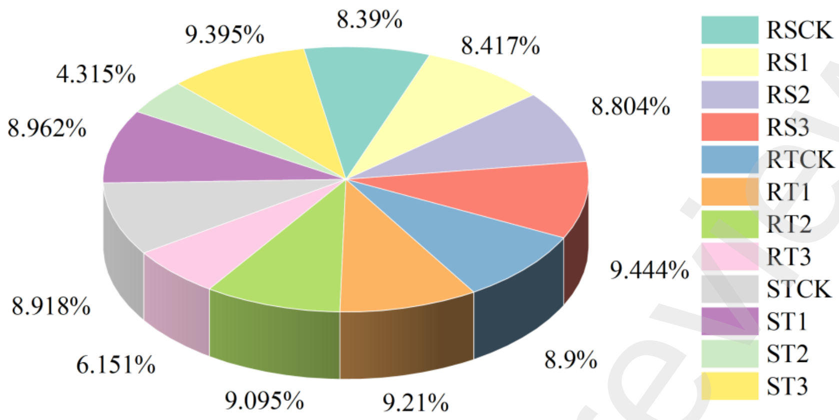

Fig 12. Ranking of different treatments in TOPSIS analysis

Table 2 Ranking of different treatments in TOPSIS analysis

Farming method	D_i^+	D_i^-	C_i	Order
RSCK	0.245044968	0.209801813	0.461258212	10
RS1	0.198985602	0.171374807	0.462724424	9
RS2	0.185942183	0.174426287	0.484022053	8
RS3	0.220969248	0.238611425	0.519193776	1
RTCK	0.237662195	0.227701688	0.489298153	7
RT1	0.182878932	0.187576481	0.506340235	3
RT2	0.18523272	0.185255179	0.50003031	4
RT3	0.266257546	0.13603161	0.338143865	11
STCK	0.242905256	0.233655849	0.490295675	6
ST1	0.192265722	0.18673542	0.492704109	5
ST2	0.268503968	0.083511168	0.237237436	12
ST3	0.225124695	0.240506022	0.516516659	2

It can be seen from Fig. 12 and Table 2 that the ranking of each scheme was obtained by analysing each treatment through the combination weight-TOPSIS analysis method, indicating that RS3 had the optimal comprehensive score and took the lead in improving soil properties and greenhouse gas reduction. ST3 was the scheme second only to RT3, and there was no significant difference in the comprehensive score from RS3. Thus, it can be concluded that the application of 3 t/hm² biochar had the highest effect on soil properties and greenhouse gas reduction. In addition, most of the rankings of biochar treatments were higher than those of CK, indicating that biochar can effectively improve soil properties, enhance soil water and heat preservation capacity, and reduce greenhouse gas emissions. On the whole, the comprehensive scores of most treatments in ST and RT ranked higher than those in RS. Combined with the research in this paper, ST was superior to RT and RS in both improving soil properties and reducing greenhouse gas emissions.

4 Discussion

4.1 Response mechanism of soil water and heat dynamics

Applying different amounts of biochar enhanced the soil's water -holding capacity. This is mainly because biochar can reduce the soil bulk density, increase micropore volume, and increase available water content [21,23]. When biochar is mixed with soil, the bulk density of the resulting soil is lower than that of the original soil. This is because the increase in the space between and within pores in coarse -grained soil leads to an increase in soil moisture [24]; the porous structure of biochar contributes to enhancing the total porosity of soil, especially micropores. These micropores can store soil moisture and facilitate plants' absorption and utilisation of it. And large pores in soil provide space for the retention of microorganisms and water [25]; when biochar is added to soil, micro-aggregates in soil's combine with the biochar matrix to form large aggregates. Stable aggregates with macropores are formed by large aggregates [26], and they can boost the water content of biochar-amended soil. Under the same biochar application rate, soil water content is ST >RT >RS. This is because rotary tillage disturbs the soil more severely, damaging the soil physical structure and causing rapid water loss. In contrast to the rotary tillage treatment, stubble removal causes less soil damage, maintains a relatively intact physical structure, and retains water better. At the same time, compared with the control group, applying biochar can increase soil temperature to different extents. This is because the black biochar added to the soil enhances its heat absorption and retention capacity, thereby raising soil temperature [27]. Biochar can not only alter the colour of the surface soil but also change soil roughness, leading to changes in surface reflectance. Ultimately, it enhances radiative forcing and improves soil temperature [28]. Applying biochar can stabilise the range of soil temperature and reduce the variability of soil temperature, thus increasing soil temperature and accumulated temperature [29,30]. With the same biochar application rate, soil temperatures followed the order ST >RT >RS. This could be attributed to the significant soil disturbance caused by rotary tillage, which disrupts soil physical structure and leads to poor thermal insulation. In contrast, stubble-mulching tillage results in less soil damage, maintaining a more intact physical structure and consequently better heat preservation.

4.2 Response mechanism of the dynamic changes in soil nutrients

Biochar can be used in soil to promote nitrogen mineralisation, and a similar conclusion was drawn in this study. The contents of total nitrogen, nitrate nitrogen, and ammonium nitrogen in the soil increased significantly, indicating that the addition of biochar facilitated nitrification. Biochar reduces nitrate leaching by adsorption (such as cation exchange) and microbial denitrification [31]; this is mainly because biochar itself features a relatively high specific surface area and porosity, and when applied to the soil, it can enhance its capacity to hold nitrogen [32]. Biochar alters conditions like soil pH, moisture content, and oxygen environment, influencing the microbial activities related to nitrogen transformation, suppressing soil nitrification, and reducing nitrogen loss [33]. The input of biochar increases the demand for nitrogen by soil microorganisms and promotes nitrogen immobilisation by facilitating microbial cycling [34]; the application of biochar in farmland soil can promote microorganisms to secrete soil-cementing substances to form stable aggregates, thereby reducing nitrogen loss caused by runoff [35].

With the same biochar application rate, both total nitrogen and nitrate nitrogen contents followed the order ST >RT >RS. This is because stubble retention disturbs the soil less than rotary tillage, thereby reducing soil erosion and mineralisation losses, resulting in higher total nitrogen and nitrate nitrogen contents under stubble retention compared to rotary tillage. Compared to rotary tillage, stubble retention reduces soil disturbance while also decreasing nitrogen-fixing bacterial communities. Although nitrification rates are lower in stubble-retained soils than in rotary tillage soils, reduced denitrification losses lead to increased net accumulation of NO_3^-. With the same biochar application rate, ammonium nitrogen content followed the order: RS ＞RT ＞ ST. This is because when stubble is retained on the soil surface under no-tillage conditions, the high C/N ratio straw stimulates microbial activity, causing temporary immobilisation of soil ammonium nitrogen by microorganisms [36]. However, since no-tillage reduces soil disturbance and inhibits nitrification, ammonium nitrogen accumulation becomes more pronounced over the long term. Rotary tillage accelerates stubble decomposition through soil inversion, prompting microorganisms to rapidly consume ammonium nitrogen for metabolism. Meanwhile, tillage enhances soil aeration and promotes nitrifying bacteria activity, leading to faster conversion of ammonium nitrogen to nitrate nitrogen [37].

4.3 Response mechanism of greenhouse gas emissions from soils

This study found that the application of biochar can significantly increase soil water content and soil temperature, and these two key factors, together with the characteristics of biochar itself, regulate the emission processes of three greenhouse gases, namely soil CO_2, N_2O and CH_4. In terms of CO_2 and N_2O emissions, nitrogen is difficult to mineralise and hydrolyse and microbial substrates are insufficient at low water content, resulting in reduced CO_2 and N_2O emissions; high water content promotes nitrogen transformation, and base fertiliser provides sufficient substrates, leading to emission peaks of both; temperature elevation can also enhance microbial respiration and promote the increase of both emissions [38]; In suppressing N_2O emissions, beyond its indirect influence through hydrothermal conditions, biochar directly interferes with denitrification by enhancing the affinity of N_2O reductase (nosZ), thereby promoting the conversion of denitrification products to N_2. Additionally, as soil microorganisms decompose the labile organic carbon in biochar, they increase oxygen consumption, creating an anaerobic environment conducive to denitrifying microbial survival, which also reduces N_2O accumulation to some extent [13]. Biochar exhibits a universal inhibitory effect on CH_4 emissions, with its efficacy dependent on application rates. Firstly, its high stability restricts methanogens' access to carbon sources while enhancing soil aeration to boost methane-oxidising bacteria activity; this imbalance between the two microbial groups reduces CH_4 emissions [39]. Secondly, biochar improves soil physicochemical properties and adsorbs organic matter via its large specific surface area, thereby reducing organic carbon mineralisation [40]. Additionally, it enhances CH_4-oxidizing bacteria activity by improving soil permeability and water retention, further promoting soil CH_4 uptake [41].

RT and ST, as two typical tillage methods, can both significantly affect soil greenhouse gas (CO_2, N_2O, CH_4) emissions by changing the soil microenvironment, and their mechanisms and effects are obviously different. In terms of CO_2 emissions, the improvement of soil aeration by RT is the most critical: on the one hand, RT destroys the soil structure, increases soil porosity, reduces soil water-filled porosity, creates a more suitable living environment for aerobic microorganisms, and promotes their massive proliferation [40]; on the other hand, the soil is more fully in contact with air during RT, which will cause temperature elevation, thereby further accelerating the metabolic activities of aerobic microorganisms. Under the dual effects, the decomposition rate of soil organic carbon is significantly increased, ultimately leading to a surge in CO_2 emissions. In contrast, ST causes minimal physical disturbance to the soil, resulting in relatively gentle changes in soil aeration and temperature, and the overall microbial activity remains at a relatively stable level; therefore, CO_2 emissions are significantly lower than those of RT. In terms of N_2O emissions, the differing impacts of the two tillage methods are primarily associated with soil aeration status and the enrichment of denitrifying bacteria. By increasing soil porosity, RT enhances oxygen penetration through the soil profile, effectively inhibiting denitrifying bacterial activity since denitrification occurs under anaerobic conditions. Research by Weisskopf et al. [42] demonstrated that denitrification rates decline significantly when WFPS is below 60%. RT reduces N_2O production by increasing soil porosity to facilitate oxygen diffusion and suppress denitrifying bacterial activity. In contrast, ST, with its minimal soil disturbance, promotes N_2O emissions through two mechanisms: crop residue input provides abundant carbon sources for microorganisms, while localised anaerobic microenvironments readily form in the soil, selectively enriching denitrifying bacteria [43]. For CH_4 emissions, soil structure regulation of methane-oxidising and methanogenic bacterial activity is a core factor. Reduced tillage (RT) disrupts soil aggregates, exposing methane-oxidizing bacteria to desiccation and ultraviolet radiation, thereby decreasing CH_4 oxidation capacity [44]. Additionally, RT causes uneven soil pore distribution, which readily forms localised anaerobic zones after rainfall, creating favourable conditions for methanogenic bacterial activity and further promoting CH_4 production. In contrast, conventional tillage (ST) effectively preserves the original soil structure by not only shielding methane-oxidising bacteria from adverse environments but also providing stable habitats, resulting in significantly higher CH_4 oxidation capacity in surface soils compared to RT while reducing the formation of localised anaerobic zones [45]. Consequently, CH_4 emissions under ST are lower than those under RT.

5 Conclusion

This study analysed the response characteristics of soil hydrothermal environment, total nitrogen, nitrate nitrogen, ammonium nitrogen, and greenhouse gases under different tillage methods and biochar application rates through field testing. The results showed that the application of biochar could effectively improve soil hydrothermal conditions, enhance soil water-holding capacity, regulate soil temperature, and optimise soil structure. Among them, the biochar application rate of 3 t/hm^2 showed significant advantages in improving soil hydrothermal conditions and increasing soil total nitrogen, nitrate nitrogen, and ammonium nitrogen contents. At the same time, this measure could also increase soil CO_2 emissions, reduce N_2O emissions and promote CH_4 absorption; RS, RT and ST tillage methods could all reduce soil damage, enhance soil structural stability and play a positive role in optimising soil hydrothermal conditions, increasing soil nitrogen (total nitrogen, nitrate nitrogen, ammonium nitrogen) contents and regulating greenhouse gas emissions such as CO_2, N_2O and CH_4, and the effects of different tillage methods were different, among which the comprehensive effect of ST treatment was better than that of RT and RS treatments. Furthermore, the combination weight-TOPSIS comprehensive evaluation method was used to conduct an assessment on each treatment scheme. The results showed that the RS3 scheme was the optimal scheme for improving soil properties and reducing greenhouse gas emissions. In conclusion, the synergistic application of tillage methods and biochar is of great significance in improving soil properties, reducing greenhouse gas emissions, studying soil resilience, and promoting emission reduction practices, and also provides a practical basis for subsequent research related to soil properties and greenhouse gases.

Data Availability Statement

All data used in this study are available from the corresponding author upon request.

CRediT authorship contribution statement

Xinru Li: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. **Zhaoxing Xiao:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review and editing. **Fanxiang Meng:** Conceptualization, Formal analysis, Funding acquisition. **Gang Li:** Conceptualization, Formal analysis. **Tianxiao Li:** Methodology. **Ennan Zheng:** Investigation, Validation. **Mo Li:** Supervision, Validation. **Jin Wang:** Validation. **Yiming Fan:** Supervision, Validation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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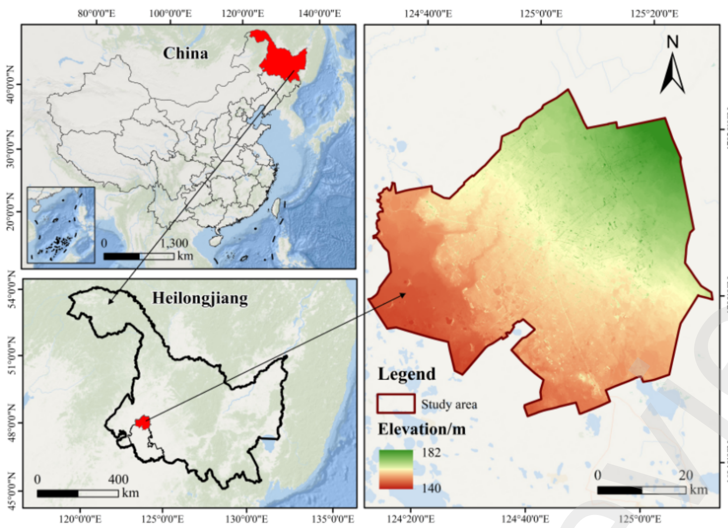

Fig.1 Survey of the study area

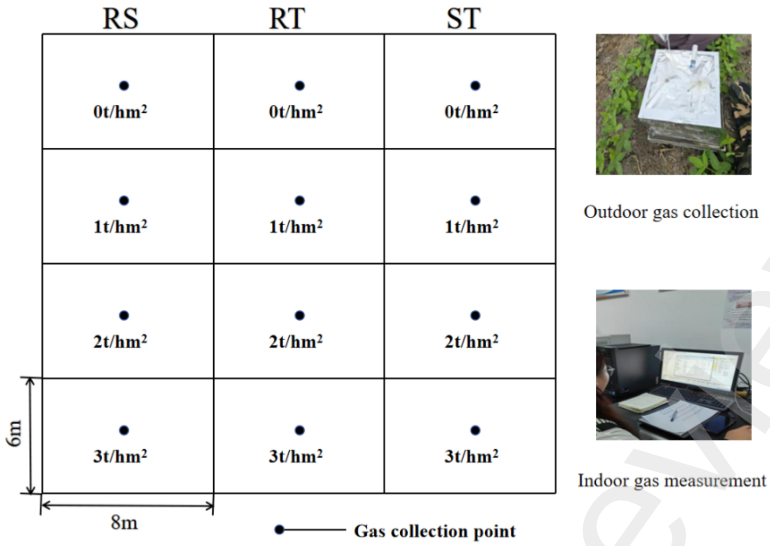

Fig.2 Experimental design diagram

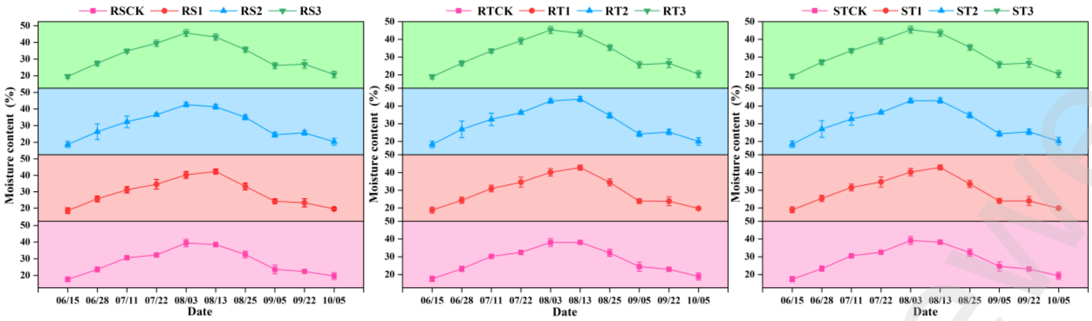

Fig. 3 Trends in soil moisture content under different treatments

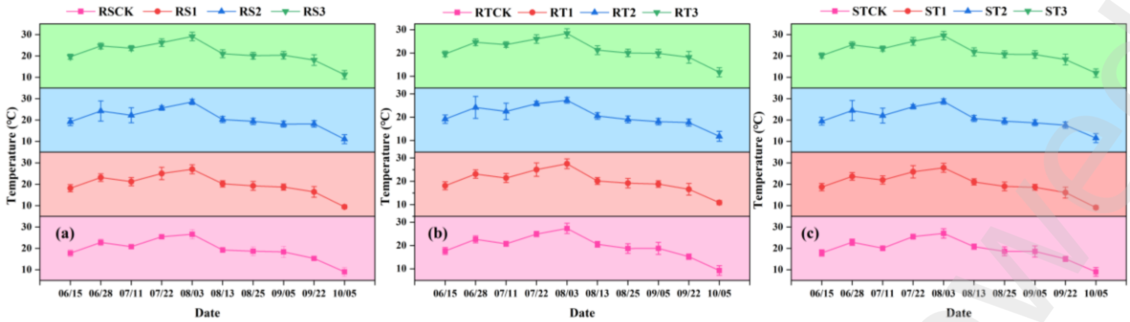

Fig. 4 Trends in soil temperature changes under different treatments

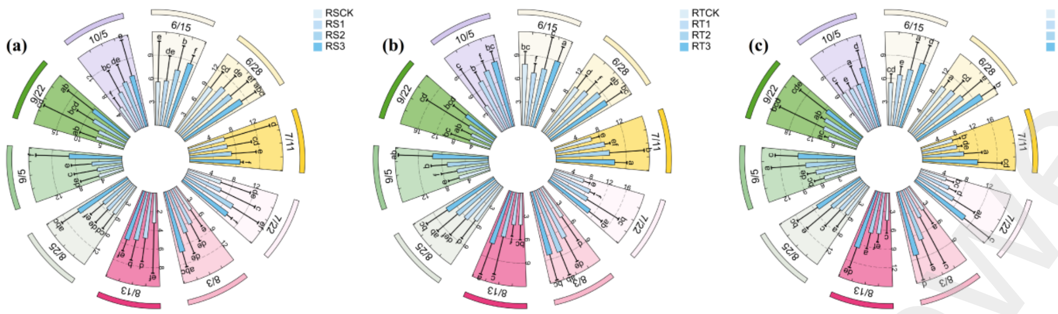

Fig. 5 Changes in soil total nitrogen under different treatments

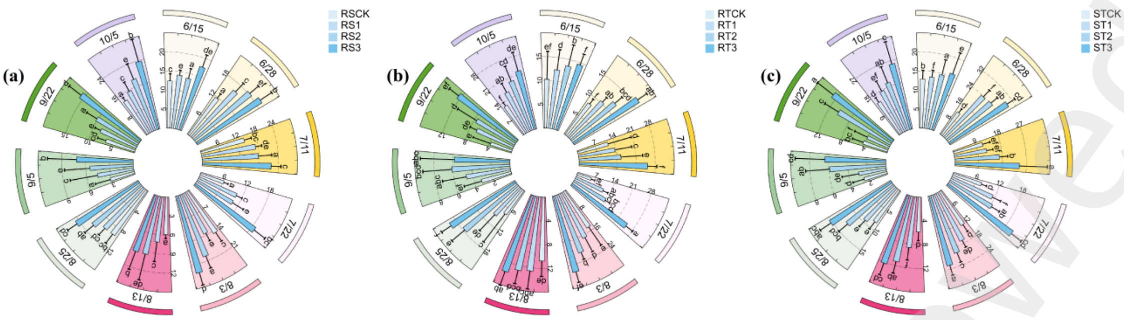

Fig. 6 Changes in soil nitrate nitrogen under different treatments

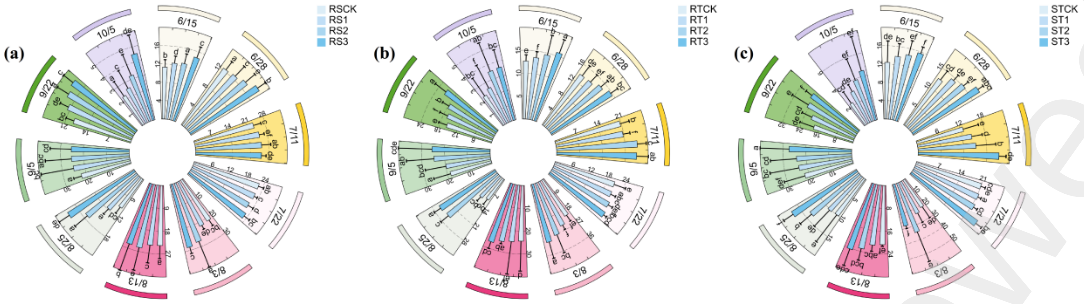

Fig. 7 Changes in soil ammonium nitrogen under different treatments

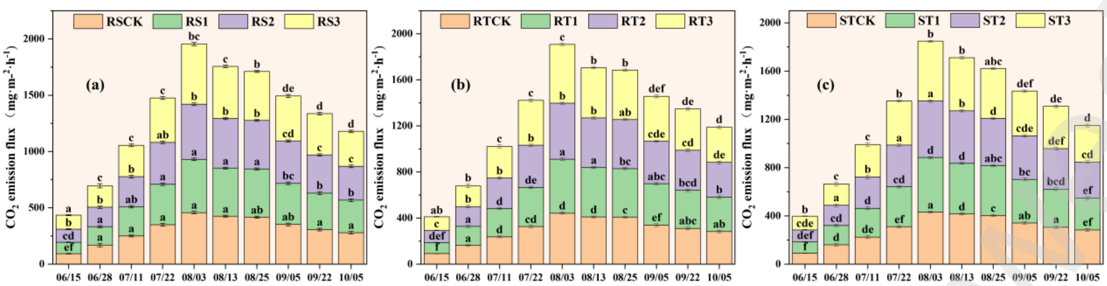

Fig. 8 CO_2 emission flux under different treatments

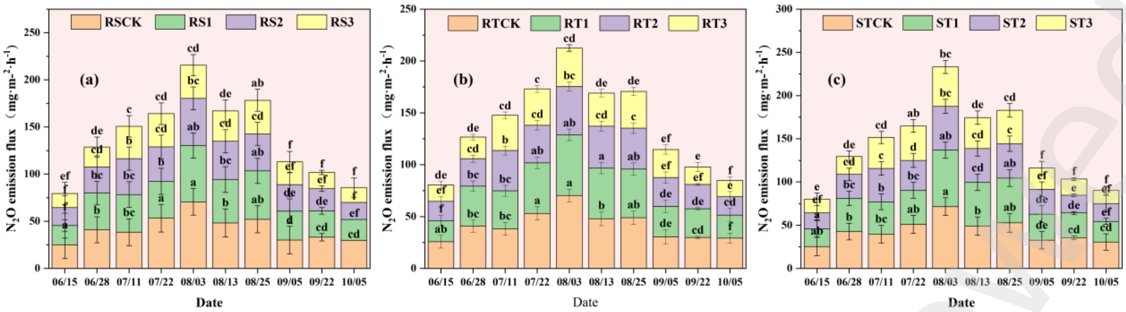

Fig. 9 N_2O emission flux under different treatments

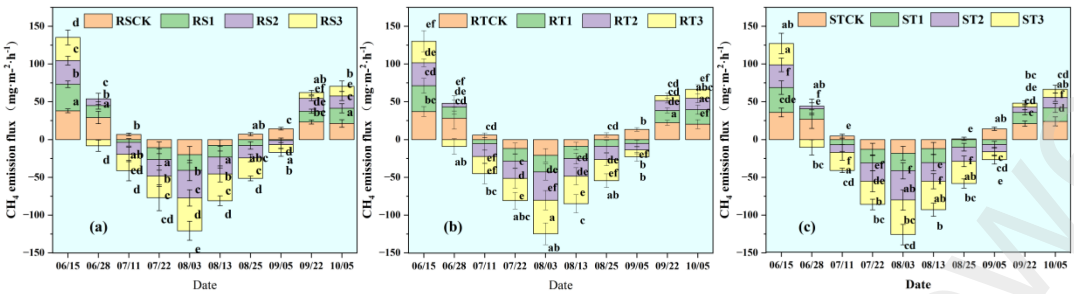

Fig. 10 CH_4 emission flux under different treatments

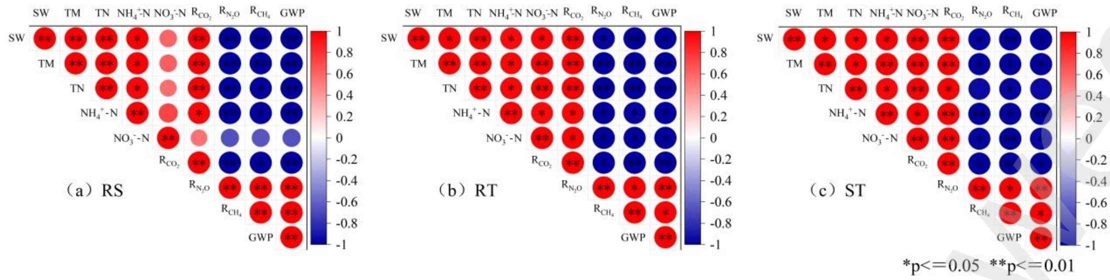

Fig. 11 Correlation analysis of CO_2, N_2O and CH_4 emission fluxes with soil moisture content, temperature, total nitrogen, nitrate nitrogen, ammonium nitrogen, and GWP under different treatments

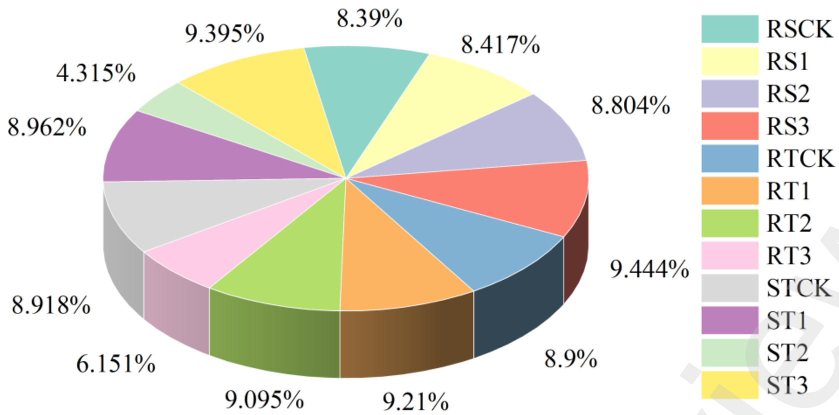

Fig 12. Ranking of different treatments in TOPSIS analysis

Table 1 GWP and cumulative emissions of CO_2, CH_4, N_2O under different treatments

Treatments	R_{CO_2}（kg·ha^{-1}）	R_{N_2O}（kg·ha^{-1}）	R_{CH_4}（kg·ha^{-1}）	GWP（kg CO_2-eq ha^{-1}）
RSCK	5816.86±322.87bc	798.39±0.04ab	140.85±0.02a	247423.26±332.18bc
RS1	5979.93±223.61de	720.66±0.07a	-32.64±0.04ab	219921.71±242.39de
RS2	6195.89±262.87cd	161.01±0.04ab	-161.02±0.05ab	178681.55±268.98bc
RS3	6557.47±489.69a	541.96±0.04ab	-297.38±0.02c	160626.61±495.57a
STCK	5643.50±336.69bc	779.92±0.17ab	157.86±0.02ab	242006.94±354.57bc
ST1	5911.19±278.68ef	704.07±0.14ab	-7.89.±0.03ab	215526.66±291.93ef
ST2	6142.69±250.33de	599.62±0.13bc	-142.69±0.03bc	181263.08±267.05de
ST3	6362.82±392.53a	495.86±0.09d	-275.54±0.02c	147329.01±401.91a
RTCK	5556.60±284.25cd	764.75±0.04ab	175.82±0.02ab	237840.10±293.61bc
RT1	5734.36±213.46f	705.80±0.05ab	11.32±0.03ab	216346.78±226.84f
RT2	5910.81±256.18de	590.224±0.04bc	-106.21±0.02bc	179172.16±265.74de
RT3	6183.40±376.33ab	502.42±0.05cd	-206.9941±0.04c	149380.21±389.73ab

Table 2 Ranking of different treatments in TOPSIS analysis

Farming method	D_i^+	D_i^-	C_i	Order
RSCK	0.245044968	0.209801813	0.461258212	10
RS1	0.198985602	0.171374807	0.462724424	9
RS2	0.185942183	0.174426287	0.484022053	8
RS3	0.220969248	0.238611425	0.519193776	1
RTCK	0.237662195	0.227701688	0.489298153	7
RT1	0.182878932	0.187576481	0.506340235	3
RT2	0.18523272	0.185255179	0.50003031	4
RT3	0.266257546	0.13603161	0.338143865	11
STCK	0.242905256	0.233655849	0.490295675	6
ST1	0.192265722	0.18673542	0.492704109	5
ST2	0.268503968	0.083511168	0.237237436	12
ST3	0.225124695	0.240506022	0.516516659	2