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Optimizing N-fertigation scheduling maintains yield and mitigates global warming potential of winter wheat field in North China Plain

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ABSTRACT

Traditional methods of nitrogen fertilizer (urea) application are major causes of poor nitrogen use and serious greenhouse gas emissions (GHG), which translates into global warming. Rational scheduling of nitrogen fertilization is critical for the mitigation of greenhouse gas emissions as well as ensuring sustainable food production. There is little information on the coupled analysis of global warming potential (GWP) and grain yield (GY) of winter wheat under a drip fertigation system. A two-year field experiment was conducted to determine the effect of split fertigation of nitrogen on GWP and yield of drip-irrigated winter wheat. The 5 levels of nitrogen schedule were as: N0-100 (all N fertilizer was applied as topdressing N), N25-75 (25% as basal N and 75% as topdressing N), N50-50 (50% as basal N and 50% as topdressing N), N75-25 (75% as basal N and 25% as topdressing N), and N100-0 (all N fertilizer was applied as basal and 0% topdressing N). The total nitrogen rate was 240 kg ha^{-1}. The basal N doses were spread just before sowing and the topdressing N doses were applied through a drip fertigation system. The results revealed that N schedule significantly ($P < 0.05$) affected GHG (CO_2, CH_4 and N_2O) emissions, GWP, GY, and subsequently the greenhouse gas intensity (GHGI). The lowest GWP (125.34 kg CO_2 eq. ha^{-1}) and GHGI (15.01 kg CO_2 eq. Mg-1) were observed in N50–50 and N25-75 N scheduling, respectively. Compared with N100-0, the N scheduling of N25–75 and N50-50 significantly ($P < 0.05$) reduced GWP by 67.67 and 63.48%, respectively. A significantly higher yield (9.09 tons ha^{-1}) was observed in the N50-50 treatment. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) specified that N50-50 N schedule provides the best results for minimized GWP at an acceptable GY. Therefore, the scheduling of 50% applied as basal N and other 50% as topdressing N through N-fertigation would be recommended for sustainable wheat production at a reduced risk of global warming in the North China Plain.

1. Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) serve to protect the earth from being excessively warm by capturing the solar radiation reflecting into the atmosphere. However, due to the burning of fossil fuels, population growth, agricultural and other economic activities, the amount of these gases in the atmosphere has increased dramatically in the past decades, resulting in an abnormal increase in global temperatures (Aydin et al., 2012). Agricultural activities, generally, increase the total amount of these gases in the atmosphere (Wei et al., 2018), and the application of chemical fertilizers contributes up to 38% of crop fields global warming potential (Guardia et al., 2019). Therefore, reducing greenhouse gases (GHG) via rational fertilizer application schedules is essential for managing the threats of global warming and climate change. Greenhouse gas emissions carry the most serious threat to the environment owing to improper use of N fertilizers on croplands (Aguilera et al., 2015). Agriculture, as one of the major land use systems globally, with farming activities producing a sizable amount of GHG, constitutes challenges for research's quest to quantify and analyze the effects of fertilizer management practices on GHG

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mitigation potentials. According to previous studies, farmlands accounted for 50% and 43% of N_2O and CH_4 of total anthropogenic CO_2-equivalent emissions, respectively (Ding et al., 2017).

Winter wheat production plays a significant role in grain production in China, contributing up to 60–80% of the country's wheat output (Du et al., 2014). The North China Plain (NCP) is the domain winter wheat production area, and becomes a major source of GHG emissions due to the fact that most farmers, traditionally, apply urea fertilizer for the supply of high nitrogen to the crop to increase yield (Si et al., 2020). Contrary to the traditional methods, a designed schedule of drip fertigation of nitrogen could be an effective way for reducing GHG emissions and ensuring the sustainability of winter wheat production in the NCP.

Nitrogen input is the major agricultural management practice that enriches the soil mineral nitrogen, an important factor affecting soil GHG emissions (Li et al., 2020). Typically, N_2O is affected by nitrification and denitrification processes, which are influenced by mineral nitrogen excessively introduced to the soil by improper fertilization (Álvaro-Fuentes et al., 2016). When N input exceeds the optimal level, an increase in N_2O emission usually occurs, which is associated with a decrease in nitrogen use efficiency (Ning et al., 2019). Fortunately, rational use of nitrogen fertilizer could help reduce the emission of N_2O in soils and maintain a healthy environment for crop production sustainability (Trost et al., 2016; Bronson et al., 2018). The effect of nitrogen application on CO_2 emission mainly depends on the content of soil organic matter. When the soil carbon source is sufficient, the application of nitrogen fertilizer can increase soil respiration and therefore initiate CO_2 emission. But when the soil carbon source is insufficient, nitrogen fertilizer can inhibit soil respiration (Oertel et al., 2016). Agricultural soils could emit or sink CH_4, depending on the oxygen supply to soil microbial organisms (Álvaro-Fuentes et al., 2016). In non-wetland soils, CH_4 uptake may occur through oxidation where methanotrophs utilize the CH_4 as a carbon source and transform it into CO_2 (Mehmood et al., 2021).

Using N fertilizers (urea) on croplands to improve yield has witnessed a considerable rise recently, leading to an increase in the amount of GHG emissions released into the atmosphere (Sun et al., 2020). The highly expensive organic and slow-release fertilizers proposed by some studies are less likely capable of replacing the cheaper urea fertilizers in the short run. Therefore, a designed schedule of split application of urea fertilizers applied via the drip irrigation system could be a reliable option for achieving a sustained production and mitigated GHG emissions. Soil inorganic nitrogen was found to significantly correlate with GHG emissions in N fertilizer trials (Zhang et al., 2021), but its quantity and distribution in the soil could be influenced by a split fertigation program of N-fertilizer. The influence of other factors, such as soil moisture, on GHG emissions could be controlled by water-saving irrigation techniques such as drip irrigation (Franco-Luesma et al., 2020). Studies found that chemical processes like soil respiration, nitrification and denitrification are inhibited under drip irrigation (Mehmood et al., 2019). Drip irrigation has proven to be an effective way of resource conservation, enabling efficient water and fertilizer use (Kumar and Palanisami, 2010; Van der Kooij et al., 2013; Zhang et al., 2020). The integration of drip irrigation with fertigation systems provides more accurate crop nutrients and improved nitrogen fertilizer use efficiency than the traditional, direct broadcasting fertilization practiced by most farmers in the NCP (Tian et al., 2017). Fertigation enables proper placement and timing of nutrients' supply to the crops root zone. Therefore, it is believed that the efforts to mitigate agricultural GHG emissions could be focused on managing fertilizer use through scheduled drip fertigation.

Many studies have been carried out on GHG emissions from farmland under furrow irrigation, flood irrigation, and even drip irrigation (Kallenbach et al., 2010; Zhong et al., 2021), but only a few results have been reported on drip fertigation systems and their influences on effective nitrogen application of drip-irrigated winter wheat fields in respect of yield maintenance and GHG emissions mitigation in the NCP (Wang et al., 2016; Wei et al., 2021; Jamali et al., 2021). Furthermore, field experimental results on split scheduling of nitrogen in drip fertigation systems and their relation with wheat grain yield and GHG emissions are grossly limited (Zhang et al., 2021). Therefore, more new knowledge is necessary for an optimum nitrogen fertigation schedule that may mitigate GHG emissions and stabilize crop yield in drip-irrigated winter wheat. This study aims to evaluate the effects of various split application schedules on GHG emissions and wheat grain yield with a certain nitrogen rate, recommended by many recent works (Si et al., 2020; Zhang et al., 2021; Duan et al., 2019), under a drip fertigation system. The study will also aim to use a comprehensive evaluation technique to establish the optimum nitrogen scheduling under drip irrigation fertigation for balancing GHG mitigation and acceptable winter wheat yield in the NCP. The results of this study will provide the basis for knowledge-based N fertigation scheduling management in drip-irrigated winter wheat fields of the North China Plain.

2. Materials and methods

2.1. Research location

The field experiment was carried out in Xinxiang comprehensive experimental station of Chinese Academy of Agricultural Sciences, located in Qiliying, Xinxiang, Henan (35.08° N, 113.45° E, and an elevation of 77 m above sea level). The total precipitation received were 113.00 mm and 87.00 mm for 2019/2020 and 2020/2021 winter wheat growing season, respectively (Fig. 1), and the average temperatures were 10.39 °C and 10.45 °C, respectively. Soil available N, P, and K contents of the cultivated layer (0–20 cm) are 80.50 mg kg^{-1}, 10.53 mg kg^{-1} and 217.00 mg kg^{-1}, respectively, and soil organic matter content was 1.88%. The water table was about 12 m below the soil surface. Other soil physical properties were as described in Zain et al. (2021).

2.2. Experimental design and field practices

Five N-fertigation levels were set in a randomized complete block design experiment. All treatments were replicated three times. Each plot was 3 m by 15 m in size and an access space of 0.5 m was allowed between the blocks. Crop variety, seedbed preparation, weed and pests and disease control were similar to Si et al. (2020) and the same for all blocks. The detailed fertilization schedules for different N-fertigation levels are shown in Table 1. The total N application rate of 240 kg ha^{-1} was selected as recommended by recent experimental works (Zhou et al., 2017; Zhang et al., 2021). Irrigation was done to bring the soil water content to field capacity while 40% moisture depletion within the soil layer of 0–60 cm was allowed. Fertigation of topdressing nitrogen

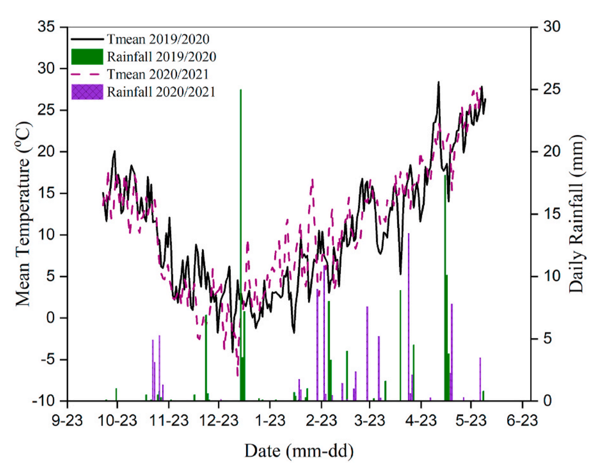


Fig. 1. Daily rainfall and temperature in research site during two winter wheat seasons. Tmean = Mean daily temperature.

Table 1
Description of N-fertilizer schedules of the experimental treatments.

Treatment code	Nitrogen (urea) fertilizer schedules (kg N ha^{-1})		
	Before sowing	Jointing[a]	Booting[a]
N0-100	0	120	120
N25-75	60	90	90
N50-50	120	60	60
N75-25	180	30	30
N100-0	240	0	0

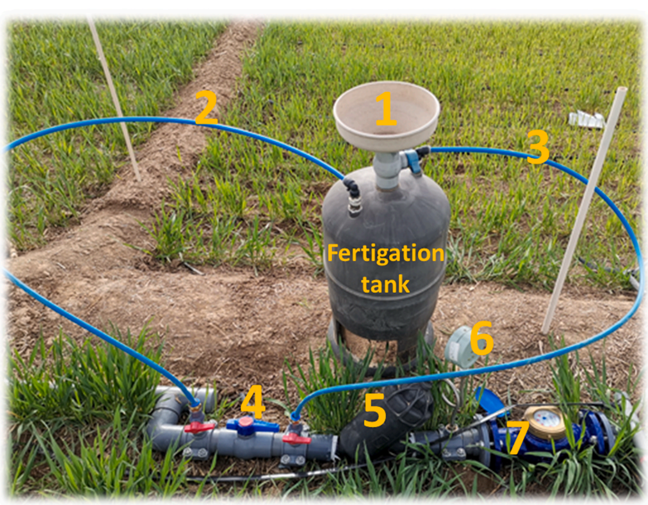
[a] N fertilizer was applied using a fertigation system.

was done at the jointing (middle of March) and booting (middle of April) stages of the winter wheat. Other details on irrigation and fertigation management were as described by Ning et al. (2019). The fertigation system used is shown in Fig. 2. The local domain high-yield winter wheat variety "Aikang-58" was sown at 180 kg ha^{-1} of seeds (20 cm row spacing) on October 23, 2019 and October 24, 2020, and was harvested on June 1, 2020 and June 2, 2021, respectively.

2.3. Gas sampling and analysis

The methods of quantifying the concentrations of CO_2, CH_4 and N_2O between landscape and atmosphere can be classified into two categories: chamber and micrometeorological (Denmead, 2008). The chamber method is dominant and suitable for small farming settings because of its adaptability, portability, affordability, and flexibility to the various production environment. This technique was developed more than 80 years ago and is used in about 95% of the various publications of emission studies (N_2O specifically) (Mosier et al., 1996; Rochette and McGinn, 2005).

The static chamber system used in this experiment was made up of a Steel frame, which was permanently installed into the ground, a chamber box (opaque PVC), equipped with a battery-powered fan and an access tube for the gas collection. The size of the box was 50 m (height) × 50 m (width) × 50 m (length). The height of the gas sampling box was adjusted to 80 cm to accommodate the wheat height at its later growth stages. Sampling started two days after sowing with two



Key components:	Running process:
1. Funnel	A. Fertilizer solution is supplied to the fertigation tank through the funnel
2. Inlet hose	B. The choke valve is closed to divert flow through the tank via the inlet hose
3. Outlet hose	C. Fertigation begins via the outlet hose for a period of time required to release the volume of the tank
4. Choke valve	D. The system is disconnected to drain the tank
5. Filter	
6. Pressure gauge	
7. Flow meter	

Fig. 2. Schematic diagram of the drip fertigation system connected to the drip sub-main line at the experimental site.

sampling events per week taken in the morning (9:00–11:00) of each sampling day. The frequency of sampling was increased to every 24 h after fertilization or fertigation. The samples were analyzed within 24 h using a gas chromatograph system (Shimadzu 2010 Plus, Shimadzu CO., Ltd., Kyoto, Japan). CO_2 and CH_4 concentrations were measured by the FID detector, while the ECD detector was used for N_2O concentration. Gas concentrations were measured in ppm and converted to emission flux (mg m^{-2} h^{-1}) using a calibration equation (Eq. (1)) at standard gas parameters. Other protocols were as described by (Mehmood, 2019).

$$J = \frac{dc}{dt} \times \frac{M}{V_o} \times \frac{P}{P_o} \times \frac{T_o}{T} H \quad (1)$$

Where: J is emission flux (mg m^{-2} h^{-1}), dc/dt is the slope of the linear regression of gas concentration at the time approaching zero, M is the molar mass of the measured gas (g mol^{-1}), P is the atmospheric pressure (Pa), T is the absolute temperature (K) inside the chamber; V_o, P_o, T_o is the volume (ml), pressure (P_a) and absolute temperature (K) at standard condition, H is chamber height above the soil surface (cm).

Cumulative emissions of GHG were calculated with eq. 2

$$CE = \sum_{i=1}^{n} \left[\left(\frac{F_i + F_{i+1}}{2} \right) \times 10^{-3} \times \Delta d \times 24 \times 10 \right] \quad (2)$$

where CE is the total cumulative GHG emissions (kg ha^{-1}), n = the number of samplings, F_i and F_{i+1} are the measured fluxes at two consecutive sampling events (mg m^{-2} h^{-1}), and Δd is the number of days between two sampling events.

The global warming potential (GWP) of GHG emissions based on the Intergovernmental Pannel on Climate Change (IPCC) for 100 years was estimated using eq. (3) (Zhang et al., 2021)

$$GWP \ (\text{kg} \ CO_2eq.ha^{-1}) = 265 \times CE_{N_2O} (\text{kg} \ ha^{-1}) + 28 \times CE_{CH_4} (\text{kg} \ ha^{-1}) \quad (3)$$

The greenhouse gas emission intensity (GHGI) was calculated with eq. (4)

$$GHGI \ (\text{kg} \ CO_2eq.Mg^{-1} \ grain) = \frac{GWP}{grain \ yiled} \quad (4)$$

2.4. Soil sampling and analysis

During gas sampling, soil samples at a depth of 0–10 cm were collected at points close to the static chamber to analyze the soil water and inorganic nitrogen (NH_4^+-N and NO_3^--N) contents. The soil moisture was determined using the gravimetric method after the samples have been oven-dried for 24 h at 105 °C. Ammonium nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N) were determined with a continuous automatic flow analyzer as described by Ning et al. (2019). The soil temperatures at a depth of 5 cm were also measured using digital thermometers. The summary of the steps involved in this methodology is shown in Fig. 3.

2.5. Determination of wheat grain yield

An undisturbed area (1 m^2) was randomly sampled from each treatment block for harvesting. The wheat was air-dried and threshed manually to determine the grain yield. The actual yield was then expressed in tons per hectare at 12% moisture content.

2.6. Determination of optimum nitrogen scheduling using TOPSIS

To evaluate the optimum N-fertigation treatment, which balances the negative effect to GWP with the positive benefit to GY, a multi-objective optimization method known as the "Technique for Order of Preference by Similarity to Ideal Solution"-TOPSIS (Lai and Hwang, 1994) was employed. The steps involved were as follows:

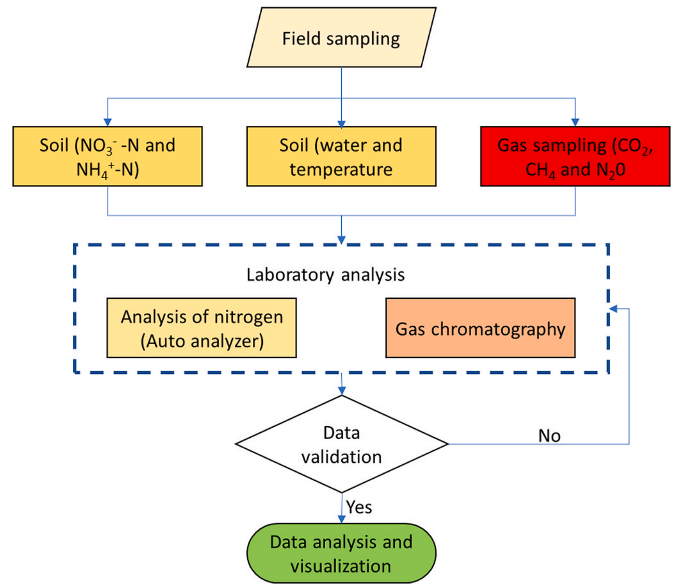


Fig. 3. Flow chart of the research methodology.

1. Establishing the contribution matrix of the evaluation indices (in this case, GWP and GY) with Eq. 5

$$X = (X_{ij})_{n\times m} \tag{5}$$

In which, m is the number of N-fertigation treatments; n is the number of the evaluation objectives; X_{ij} contribution value of the ith N-fertigation to the jth evaluation index.

2. Calculating the normalized matrix (Eq. (6)):

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=0}^{n} X_{ij}^2}} \quad i = 1, 2, \ldots, n; j = 1, 2, \ldots, m \tag{6}$$

3. Calculating the weighted normalized matrix (Eq. (7)):

$$V_{ij} = \overline{X}_{ij} \times W_j \tag{7}$$

Positive V_{ij} is the ideal best while negative V_{ij} is the ideal worst case.

W_j = weight of the jth criterion such that $\sum_{j=1}^{n} W_j = 1$; for this work, GWP was given the weight of 0.5, while GY was set to be 0.5 to balance their respective contributions.

4. Calculating the Euclidean distances (Eqs. (8) and (9)):

$$d_i^+ = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2} \tag{8}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2} \tag{9}$$

5. Calculating the performance score of the treatments (Eq. (10))

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{10}$$

2.7. Statistical analysis

The variations in cumulative means of CO_2, CH_4 and N_2O emissions under different fertigation levels were analyzed by one-way ANOVA and Fisher's LSD test at the probability of 95% in the Minitab 19 statistical software (State College Pennsylvania, USA). Pearson's correlation analysis was used to determine the relationship between environmental variables and seasonal means of GHG. Repeated-measures ANOVA was conducted in the SPSS 23.0 (SPSS, Chicago, Illinois, USA) software to analyze the effect of the sampling dates and their interactions with the experimental treatments. The graphs were created using GraphPad Prism version 9.1.0 for Windows (GraphPad Software, San Diego, California USA).

3. Results

3.1. Seasonal variations of soil inorganic nitrogen under different N-fertigation scheduling

N-fertigation affected the temporal variation of the soil inorganic nitrogen during the 2019/2020 and 2020/2021 seasons (Fig. 4). All treatments showed a similar pattern, and peak concentrations of inorganic nitrogen were observed just after fertilizer application in both growing seasons. Inorganic N increased with the increase in the proportion of basal nitrogen, which is more significant for NO_3^--N. Therefore, N100-0 recorded a significantly ($P < 0.05$) higher average of inorganic nitrogen in both seasons. However, after topdressing N applications, obvious increases in the concentration of inorganic nitrogen were observed in the N0-100 treatment, which is more obvious for NH_4^+-N. Generally, the highest proportion of basal or topdressing N increased the average concentration of inorganic nitrogen in both seasons. Overall, N100-0 increased the inorganic nitrogen content by 32% as compared to N25-75.

3.2. Seasonal variations and cumulative GHG emissions under different N-fertigation scheduling

3.2.1. Seasonal dynamics of CO_2 emission

The variation patterns of all treatments were generally similar, and a slight trend may be checked that higher CO_2 emission in early stages under a higher proportion of basal N, and in late stages under a higher proportion of topdressing N (Fig. 5a and d). Sudden rises in CO_2 emission were observed immediately after fertilization and fertigation in both 2019/2020 and 2020/2021 growing seasons. The effects of fertigation on the pattern of the CO_2 curves were more obvious in the higher fertigation treatments such as N0-100 and N25-75. The repeated measures ANOVA (Table 2) showed that the N-fertigation treatments (N), sampling dates (SD) and their interaction affected significantly the daily CO_2 emissions ($P < 0.05$). The highest rate of CO_2 emissions was observed after the second topdressing applications in both seasons. Maximum emissions rates of 954.24 mg m^{-2} h^{-1} and 735.34 mg m^{-2} h^{-1} were respectively observed in 2019/2020 and 2020/2021 seasons for N0-100 treatment.

3.2.2. Cumulative CO_2 emission

The statistical analysis revealed that different N-fertigation treatments significantly ($P < 0.05$) influenced the means of the cumulative CO_2 (CE_{CO2}) emissions (Table 3). The maximum CE_{CO2} was observed in N0-100 as 11379.84 kg ha^{-1} and 12373.12 kg ha^{-1} in 2019/2020 and 2020/2021, respectively. However, the minimum values of 9277.24 kg ha^{-1} was obtained under N75-25 in 2019/2020 season and 10154.68 kg ha^{-1} under N100-0 in 2020–2021 season. Based on the average of two

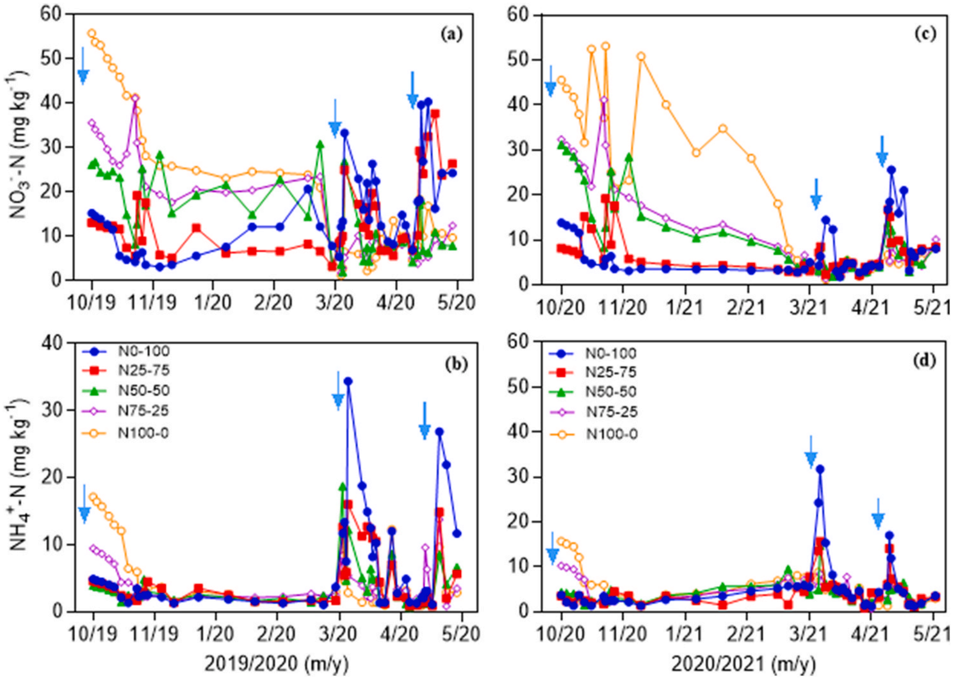


Fig. 4. Variations of NO_3^--N and NH_4^+-N concentrations under different N-scheduling treatments for (a and b) 2019/2020 and (c and d) 2020/2021winter wheat growing seasons. Each data point represents the average of three replicates. The downward arrows indicate the date of N fertilizer application.

seasons, the N75-25 decreased the CE_{CO2} emission by 18.19% as compared to N0-100. However, N100–0 and N50-50 were not significantly different ($P > 0.05$). The order of CE_{CO2} change was N0-100 > N25-75 > N50-50 > N100-0 > N75-25.

3.2.3. Seasonal dynamics of CH_4 emission

The seasonal variations of daily CH_4 uptake were presented in Fig. 5b and e. The negative values indicate the ability of the soil to sink the CH_4 gases. The N-fertigation treatments significantly ($P < 0.05$) influenced the rates of CH_4 uptake. The pattern of variation in the CH_4 uptake was largely similar between the two seasons. It could be observed that there were obvious increases in CH_4 uptake after fertigation of the topdressing nitrogen. The N0-100 treatment showed higher CH_4 uptake for the majority of the wheat growth period in the two seasons. In 2019/2020 and 2020/2021, both maximum uptakes of 628.5 and 376.4 μg m^{-2} h^{-1} were observed in N0-100. The order of daily CH_4 uptake in the five treatments was N100-0 < N75-25 < N50-50 < N25-75 < N0-100, which showed an obvious trend that daily CH_4 uptake increased with the proportion of topdressing N. The treatments, sampling date (SD) and their interaction significantly ($P < 0.001$) affected the daily CH_4 emissions based on repeated measures ANOVA (Table 2).

3.2.4. Cumulative CH_4 emission

Analysis of cumulative CH_4 (CE_{CH4}) emissions for 2019/2020 and 2020/2021 suggested that the N-fertigation level affected the ability of the soil to sink CH_4 (Table 3). The CE_{CH4} values for treatments N0-100 and N25-75 were remarkably higher than those in the other 3 treatments, and the difference between N0-100 and N25-75 was not significant ($P > 0.05$) in the two experimental seasons. The CE_{CH4} uptake was not significantly different between N0-100 and N25-75, but their values were obviously lower than the other 3 treatments in two seasons. The order of soil CH_4 uptake values was N100-0 > N75-25 > N50-50 > N0-100 > N25-75 based on the average records of the two seasons.

3.2.5. Seasonal dynamics of N_2O emission

The seasonal dynamics of daily N_2O emissions for the 2019/2020 and 2020/2021 growing seasons under different N-fertigation treatments are presented in Fig. 5c and f. The curves are generally similar in both seasons. The N_2O emission curves indicated dramatic rises after basal and topdressing (fertigation) nitrogen applications, and then gradually decreased to the lowest level. The results showed that the rate of N_2O emission increased with an increase in the proportion of topdressing N in both seasons. The maximum peak emissions were observed from N100–0 and N0-100 after basal and topdressing nitrogen application in both 2019/2020 and 2020/2021 seasons, respectively. However, the lowest peak emissions were observed from N50–50 and N75-25, respectively. The repeated measures ANOVA (Table 2) showed that N_2O was significantly ($P < 0.05$) affected by the N-fertigation ratio, sampling date and their interaction (N × SD).

3.2.6. Cumulative N_2O emission

Table 3 shows the cumulative N_2O (CE_{N2O}) emissions for the 2019/2020 and 2020/2021 seasons under different N-fertigation treatments. The N application modes significantly affected the seasonal CE_{N2O} emissions ($P < 0.05$). The statistical analysis results showed that the CE_{N2O} under N25–75 and N50-50, and those under N75-25 nad N100-0, were not significantly different ($P > 0.05$). In the 2020/2021 season, N25–75 and N100-0 were not significantly different ($P > 0.05$). Compared with N100–0, N25–75 and N50-50 respectively reduced CE_{N2O} by 46.94 and 42.2% across the two seasons.

3.3. Global warming potentials

The responses of global warming potential (GWP) to different N-fertilization treatments are shown in Table 4. The results showed that GWP under more N applied as basal fertilizer, such as N100–0 and N75-25, were significantly higher than those under more N as topdressing fertilizer, such as N50–50, N25–75 and N0-100. In 2019/2020 season,

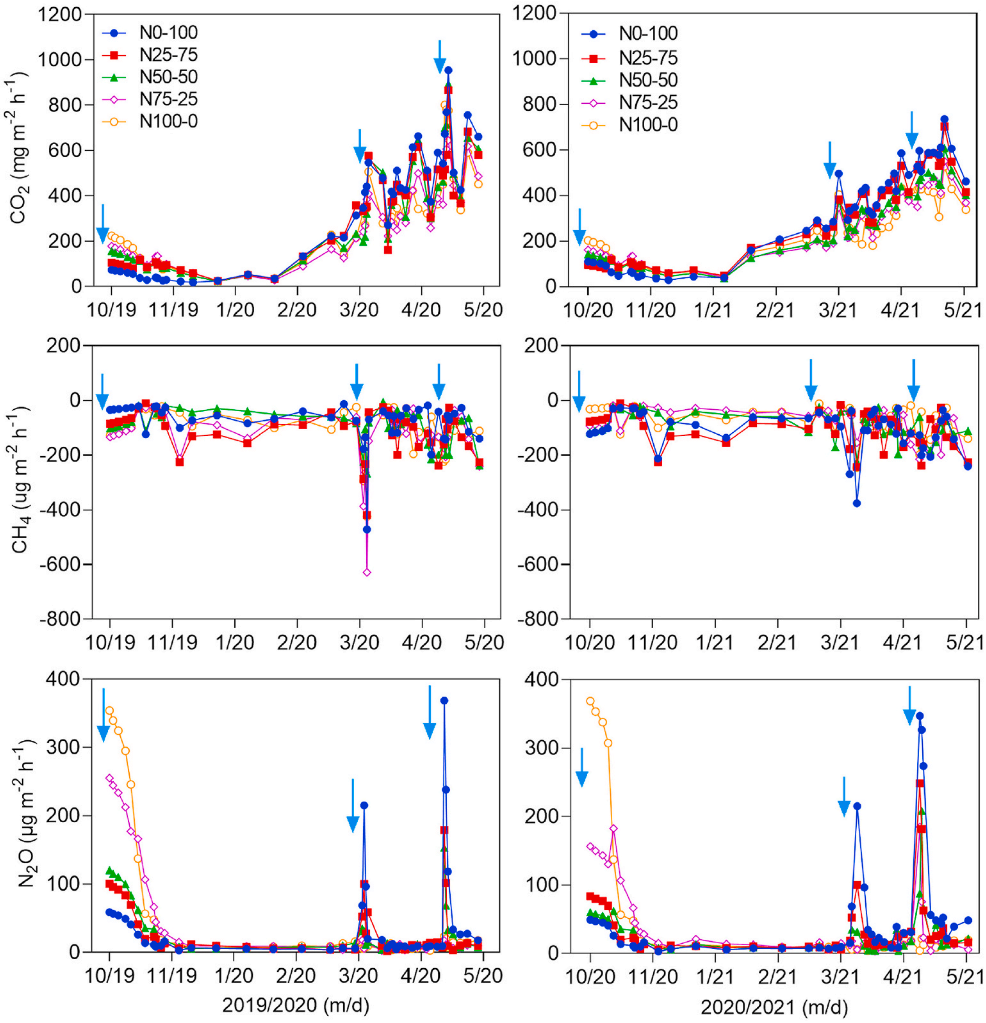


Fig. 5. Variations of CO_2, CH_4 and N_2O emissions under different N-scheduling treatments for (a, b and c) 2019/2020 and 2020/2021 (d, e and f) winter wheat growing seasons. Each data point represents the average of three replicates. The downward arrows indicate the date of N fertilizer application.

Table 2
Repeated measures ANOVA (*P*-values) for CO_2, CH_4 and N_2O as affected by N-scheduling treatments, sampling date, and their interactions.

Variables	CO_2		CH_4		N_2O	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
N	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SD	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N × SD	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: N = N-scheduling treatment; SD = sampling date.

N25-75 recorded the lowest GWP of 85.63 kg CO_2 Eq. ha^{-1}, which was significantly lower than N100-0 by 79.62% ($P < 0.05$), but similar to N0-100 and N50-50 ($P > 0.05$). Similarly, the N50–50 and N25-75 recorded lower GWP than those obtained in N100–0 and N75-25 treatments. The obvious difference occurred under N0-100, the GWP was similar to the lower values in 2019/2020 and similar to the higher values in 2020/2021 growing season. The results showed that a significant reduction in GWP could be achieved by balancing the basal and topdressing ratios of nitrogen application.

3.4. Grain yield and greenhouse gas emissions intensity

The results of the effect of N-fertigation scheduling on grain yield (GY) are also shown in Table 4. In 2019/2020 season, N50-50 treatment had significantly ($P < 0.05$) higher GY than N25–75, N75–25, N0-100, and N100-0 by 5%, 9%, 10%, and 14%, respectively. The results in 2020/2021 season are similar and the maximum yield was also observed under N50-50 treatment. Compared with N100–0, N50-50 increased GY by 22% in 2020/2021. The general trend can be described as that the balancing of N application as basal and topdressing fertilizers benefited yield maintenance, and that too high proportion of N applied as basal or topdressing fertilizers was not suitable for achieving high yield.

Table 4 also presents the effect of N-fertilization treatments on greenhouse gas emission intensity (GHGI). It was observed that in both winter wheat growing seasons, GHGI values under N100–0 and N75-25 were significantly ($P < 0.05$) higher than those under other treatments. In 2019/2020, the N25-75 treatment produced the lowest GHGI, which was 81.49% lower than under N100-0. The order of change in GHGI by treatments was N100-0 > N75–25 N > 50-50 > N0-100 > N25-75. In 2020/2021, the lowest GHGI (15.86 kg CO_2 Eq. Mg^{-1}) was obtained from N50-50 treatment but was not significantly different ($P > 0.05$) from N25-75 with 19.72 kg CO_2 Eq. Mg^{-1}. The overall results of the two

Table 3
Seasonal cumulative CO_2, CH_4 and N_2O emissions under different N-scheduling treatments for 2019/2020 and 2020/2021winter wheat growing seasons.

Season	Treatment	Cumulative emissions (kg ha^{-1})		
		CO_2	CH_4	N_2O
2019/2020	N0-100	11379.84 ± 310.45[a]	−4.91 ± 0.09[c]	0.90 ± 0.05[b]
	N25-75	11158.30 ± 548.47[ab]	−5.38 ± 0.24[c]	0.89 ± 0.04[b]
	N50-50	10854.32 ± 388.00[ab]	−4.16 ± 0.24[b]	0.95 ± 0.07[b]
	N75-25	9277.24 ± 632.10[c]	−3.48 ± 0.12[a]	1.92 ± 0.20[a]
	N100-0	9861.45 ± 456.69[bc]	−3.26 ± 0.13[a]	1.93 ± 0.28[a]
2020/2021	N0-100	12373.12 ± 214.85[a]	−5.11 ± 0.10[c]	1.58 ± 0.07[ab]
	N25-75	12124.57 ± 371.06[a]	−5.50 ± 0.28[c]	1.20 ± 0.09[bc]
	N50-50	10445.67 ± 194.6[b]	−3.92 ± 0.17[b]	0.97 ± 0.04[c]
	N75-25	10155.30 ± 139.83[b]	−3.40 ± 0.10[a]	1.52 ± 0.11[ab]
	N100-0	10154.68 ± 149.14[b]	−3.35 ± 0.07[a]	1.69 ± 0.27[a]
Mean	N0-100	11876.48 ± 262.65[a]	−5.01 ± 0.10[c]	1.24 ± 0.06[b]
	N25-75	11641.44 ± 459.77[a]	−5.44 ± 0.26[c]	1.05 ± 0.07[b]
	N50-50	10650.00 ± 291.30[b]	−4.04 ± 0.21[b]	0.96 ± 0.06[b]
	N75-25	9716.27 ± 385.97[c]	−3.44 ± 0.11[a]	1.72 ± 0.16[a]
	N100-0	10008.07 ± 302.92[bc]	−3.31 ± 0.10[a]	1.81 ± 0.28[a]

Note: Each data point represents the mean ± standard error of three replications. Different letters (superscript) indicate significant difference at $p < 0.05$.

Table 4
Seasonal means of GWP, GY and GHGI under different N-fertigation scheduling for 2019/2020 and 2020/2021 seasons.

Season	Treatment	GY (tons ha^{-1})	GWP (kg CO_2 eq. ha^{-1})	GHGI (kg CO_2 eq. Mg^{-1})
2019/2020	N0-100	7.91 ± 0.06[cd]	102.16 ± 11.65[b]	12.93 ± 1.55[b]
	N25-75	8.38 ± 0.14[b]	85.63 ± 17.42[b]	10.29 ± 2.28[b]
	N50-50	8.84 ± 0.13[a]	135.25 ± 19.71[b]	15.37 ± 2.41[b]
	N75-25	8.02 ± 0.17[bc]	412.04 ± 54.87[a]	51.41 ± 6.82[a]
	N100-0	7.57 ± 0.04[d]	420.24 ± 71.14[a]	55.62 ± 9.64[a]
2020/2021	N0-100	8.43 ± 0.2[b]	275.21 ± 21.4[ab]	32.58 ± 1.78[bc]
	N25-75	8.41 ± 0.11[b]	165.06 ± 30.85[bc]	19.72 ± 3.94[cd]
	N50-50	9.34 ± 0.22[a]	147.97 ± 6.83[c]	15.86 ± 0.83[d]
	N75-25	8.65 ± 0.16[b]	308.75 ± 32.43[a]	35.58 ± 3.13[ab]
	N100-0	7.32 ± 0.14[c]	355.37 ± 70.08[a]	48.69 ± 9.72[a]
Mean	N0-100	8.17 ± 0.09[b]	188.69 ± 15.21[b]	22.76 ± 1.45[b]
	N25-75	8.39 ± 0.12[b]	125.34 ± 24.14[b]	15.01 ± 3.11[b]
	N50-50	9.09 ± 0.18[a]	141.61 ± 12.35[b]	15.62 ± 1.59[b]
	N75-25	8.34 ± 0.12[b]	360.39 ± 43.43[a]	43.5 ± 4.96[a]
	N100-0	7.44 ± 0.07[c]	387.81 ± 70.37[a]	52.15 ± 9.68[a]

Note: GWP = the total global warming potential of N_2O and CH_4; GY = grain yield; GHGI = greenhouse gas intensity. Each data point represents the mean ± standard error of three replications. Different letters (superscript) indicate significant difference at $p < 0.05$.

seasons indicated that splitting N application as N25–75 and N50-50 could reduce GHGI by at least 71.22% and 70.05%, respectively. This strengthens the necessity of applying fertilizer during the critical growth stages of the winter wheat.

3.5. Comprehensive evaluation of nitrogen scheduling

The results of the optimization procedure, which include Euclidean distance, performance score and rank of all treatments, are shown in Table 5. Splitting total N fertilizer equally as basal and topdressing application, like under N50-50 treatment, obtained the best score of 0.939 (ranking = 1st), while N100-0 ranked 5th with the lowest score. It could be stated that N50-50 is the best N fertilizer schedule for winter wheat under drip fertigation, based on its lower release of GHG emissions to the environment and the higher grain yield.

Table 5
TOPSIS score and ranking of each N-fertigation scheduling based on balancing GWP and AGY.

Treatments	Normalized matrix		Euclidean distances		Performance	TOPSIS Rank
	GWP (w = 0.5)	AGY (w = 0.5)	d+	d-	Pi	
N0-100	0.159	0.220	0.059	0.169	0.742	3
N25-75	0.106	0.226	0.019	0.223	0.923	2
N50-50	0.119	0.245	0.014	0.212	0.939	1
N75-25	0.304	0.225	0.199	0.033	0.144	4
N100-0	0.327	0.200	0.226	0.023	0.093	5

Note: The highest rank is 1; w = Weight of the evaluation objective; GWP = Average global warming potential; AGY = Average grain yield of two seasons.

4. Discussion

4.1. Effect of N-fertigation on CO_2 emission

The results reported in this study revealed that the CO_2 emission increased with the increase of topdressing nitrogen proportion, and rapid CO_2 emission increased immediately after N-fertilizer application, which is consistent with the research results of Motavalli (2018). Bicarbonate produced after fertilization is decomposed into water and CO_2, which could be the main reason for the rise in CO_2 emission immediately after fertilization (Ge et al., 2021; Zhang et al., 2021). The increase in CO_2 emission could be a result of the activities and composition of the soil microbial community, which influenced soil and crop root respiration (Smith et al., 2008; Qiu et al., 2020). In both 2019/2020 and 2020/2021 growing seasons, a significant ($P < 0.01$) positive correlation was found between the mean CO_2 emissions and soil temperature (Table 6), which is supported by the results of Mehmood et al. (2021), Zhong et al. (2021) and Liu et al. (2021). The correlation between soil moisture and CO_2 was not significant ($P > 0.05$) as also reported by Zhong et al., (2021), who found that soil moisture did not

Table 6
Pearson correlations of the seasonal means of CO_2, CH_4 and N_2O emissions and environmental factors.

	CH_4	N_2O	Soil moisture	Soil temperature	NH_4^+-N	NO_3^--N
CO_2	−0.802**	−0.364	0.281	0.743**	−0.39	−0.435
CH_4		0.466	−0.46	−0.861**	0.724**	0.735**
N_2O			0.203	−0.415	0.662**	0.740**
Soil moisture				0.282	−0.208	−0.155
Soil temperature					−0.717**	−0.737**
NH_4^+-N						0.978**

Note: CO_2, CH_4 and N_2O are measured in (mg m^{-2} ha^{-1}); Temperature (°C); NH_4^+-N (mg kg^{-1}); NO_3^- –N (mg kg^{-1}); soil moisture (%); **correlation is significant at *P < 0.01*. n = 15.

show a significant relation with CO_2 emission. Additionally, a negative correlation between soil moisture and CO_2 emissions could be observed depending on the amount and duration of water in the soil (Wang et al., 2010). Beside, Tong et al. (2017) found that soil temperature could account for 54% of CO_2 emissions variation in wheat fields, while soil moisture could explain 22% in a 4-year experiment in the North China Plain. The effect of inorganic nitrogen was not significant ($P > 0.05$) as also observed by Zhang et al. (2021), which could be due to its negative correlation with the soil temperature (Table 6). The average range of cumulative CO_2 emissions observed in this study was consistent with the findings of Mehmood et al. (2021) and Zhang et al. (2021). The results of this study showed that the negative consequence of CO_2 emission from winter wheat fields could be mitigated by proper scheduling of nitrogen fertigation. Equal splits between basal N and topdressing N could reduce the overall CO_2 emissions from winter wheat fields.

4.2. Effect of N-fertigation on CH_4 emission

Agricultural activities such as irrigation and fertilization influence the soil ability for either taking or emitting CH_4. Higher N application may stimulate CH_4 emission by inhibiting the activity of oxidizing enzymes (Chen et al., 2016). However, in a dryland environment, the soil takes in CH_4 after a lower rate of nitrogen application (Zhang et al., 2011). This process depends on whether the oxidation process can consume (methanotrophic) the CH_4 produced by methanogenic bacteria (Mehmood et al., 2021). When the methanotrophic is overwhelmed, the soil emits CH_4 into the atmosphere. Aronson and Helliker (2010) observed that N amendment less than 100 kg N ha^{-1} yr^{-1} might stimulate the CH_4 uptake, while greater than 100 kg N $ha^{-1}yr^{-1}$ causes the inhibition of CH_4 uptake in non-wetland soils. In this study, across all the treatments, the soil served as a sink for CH_4. So, the activity of microorganisms responsible for oxidation could have been stimulated (Wu et al., 2021). The magnitude of cumulative CH_4 uptake observed was higher than that reported by Zhang et al. (2015) and Mehmood et al. (2021) because the N rate of 240 kg ha^{-1} used in this study was less than those used in their works. Moreover, this work split the total N rate into three applications via fertigation, contrary to their fertilization programs. Tan et al. (2017) reported 1.76 kg ha^{-1} as the highest soil cumulative CH_4 uptake in a three-year field experiment in North China. Their value is 58.59% lower than the average recorded by this study. Therefore, the N-fertigation approach applied in this work is effective in facilitating the CH_4 uptake characteristics of the soil. A negative and significant correlation was observed between mean CH_4 uptake and soil temperature (Table 6), which shows that temperature could have impacted the CH_4 production process as reported in the work of Zhang et al. (2020). A significant ($P < 0.01$) correlation was observed between CH_4 uptake and the soil inorganic nitrogen to indicate that the limit of the methanotrophic process was yet to be exceeded during the winter wheat growing period. Based on the mean of two years results, it could be stated that fertigation of topdressing N improves the soil ability of taking up methane until a certain threshold is exceeded.

4.3. Effect of N-fertigation on N_2O emission

Nitrogen applied in excess of the crop requirement could lead to the release of N_2O emission due to the increase of NO_3^--N and NH_4^+-N in the soil. These ions provide the substrate needed for the production of N_2O via nitrification and denitrification (Linquist et al., 2015). In this study, the NO_3^--N and NH_4^+-N under N100–0, N75–25 and N0-100 were significantly higher than those under other treatments. Therefore, there was an excess amount of nitrogen that failed to be taken by the crop and could have been used for the denitrification and nitrification processes of N_2O emission in these treatments (Maris et al., 2015). The results indicate the importance of proper N management to ensure sufficient nitrogen utilization and mitigation of N loss through N_2O emissions and other processes. There was no significant correlation between soil temperature and N_2O emissions as also reported by Liu et al. (2021) and Zhong et al. (2020) under water saving irrigation systems. A significant ($P < 0.01$) positive correlation was observed between inorganic nitrogen (NO_3^--N and NH_4^+-N) and N_2O emissions, which have also been reported by other works (Mehmood et al., 2019; Burton et al., 2008). Therefore, NO_3^--N and NH_4^+-N were the major sources of N_2O emissions across the two seasons. Other works such as Zhang et al. (2021) and Zhou et al. (2019) reported a significant relationship between N_2O emission and soil moisture. In this study, however, there was no significant ($P > 0.05$) correlation between soil moisture and N_2O (Table 6), which emphasizes the importance of the irrigation system used in the study, that is limiting the influence of moisture to the neutral level. Similar results were reported by Zhong et al., (2021), who observed a significant correlation only in full irrigation treatments (sufficient water condition). This study had a similar effect due to its water saving features as also observed by Kostyanovsky et al. (2019) in certain soils textures. Apart from the high emission rates after fertigation (irrigation + fertilization), there was no obvious rise in N_2O emission observed after irrigation or rainfall only. This could be due to the presence of relatively low inorganic nitrogen during the irrigation or rainfall event only. These results strengthen the fact that nitrogen induced higher N_2O emissions than soil moisture. Our results agreed with the findings of Schellenberg et al. (2012) that N_2O emissions caused by irrigation were practically lower than those triggered by fertilization.

The cumulative N_2O emissions observed in this study were comparable with those reported by Zhang et al. (2021) and lower than that reported by Zhong et al. (2021). These variations could be due to the differences in environmental factors and nitrogen application practices. The cumulative N_2O reported by Mehmood et al. (2019) was 20.83% percent lower than the results observed in N50-50 treatment in this study, which had the lowest N_2O emission. The difference could be due to the differences in the number and method of nitrogen fertilizer application in the two studies. N50-50 could be more suitable for mitigating GHG in a drip-irrigated wheat field, for its low N_2O emission.

4.4. Effect of N-fertigation on global warming potential

Global warming potential (GWP) is the sum of the contributions of individual CO_2-equivalent from N_2O and CH_4 as described by eq. (3). The results of this study were adequately compared with recent findings

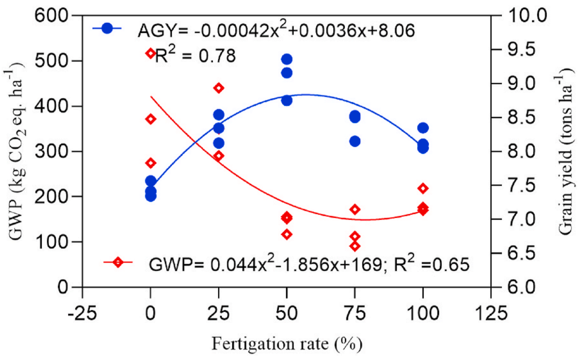


Fig. 6. Polynomial relationship for wheat grain yield and GWP for the average records of the 2019/2020 and 2020/2021 seasons under different N-fertigation rate. Fertigation rate represents the percentage of topdressing nitrogen application.

of Zhang et al. (2021), who reported a range of 253.33–331.45 kg CO_2 eq.ha^{-1}. However, since CH_4 was taken up by the soil as it is common in dryland agriculture (Mehmood et al., 2021), the majority of the GWP originated from the N_2O emissions. The range reported by Mehmood et al. (2019) is comparable to the results of this study (125.34–387.81 kg CO_2 eq.ha^{-1}). The N25–75 and N50-50 treatments recorded significantly lower GWP and could, reduce the GWP by up to 67.68 and 63.48% respectively, as compared to N100-0. It could also be observed that applying 100% nitrogen as basal fertilizer could lead to the presence of high NO_3^--N and NH_4^+-N in the soil, which encourages the process of N_2O emissions and leads to increased GWP. Fig. 6 suggests that GWP decreased as the percentage of topdressing nitrogen increases up to about 75% based on the average of the two years. For the mitigation of the global warming potential in the winter wheat fields, the basal ratio of the nitrogen fertilizer should not exceed 50% of the total 240 kg N ha^{-1}.

4.5. Effect of N-fertigation on grain yield and greenhouse gas emission intensity

The GY reported in this work was consistent with the findings of other works at the same location (Si et al., 2021; Zain et al., 2021). In line with their results, this work observed that applying 100% of N to the wheat as either basal or topdressing (fertigation) did not lead to the maximum GY, but could reduce the GY by 10–18% as compared with N50-50, respectively. Balancing a split fertilization program is therefore necessary as it would mitigate GWP and maintain a high grain yield. Fig. 6 could prove that a certain point of compromise between GWP and GY is achievable. Hence, the results of their combined responses to the N-fertigation treatments as revealed by an optimization technique is presented in Table 5.

GHGI provides a rational relationship between GHG and GY, and could serve as an index of system sustainability. The results of this work found that N100–0 and N75-25 represent the highest GHGI. They tended to increase GHGI by 71% and 66% Compared with N25-75 based on the average of the two-year records. N25–75 and N50-50 reduced GHGI by their high yield and low GHG emissions. Therefore, to mitigate GWP from winter wheat fields, nitrogen management should be centered to find the precise N-scheduling practice that increases yield and reduces GHG emissions simultaneously.

4.6. Optimized N-fertigation schedule

To achieve the goal of reducing GWP while maintaining a relatively high GY, an optimization procedure could be applied by one or more multi-objective decision methods as employed by Zhong et al., (2021) in a deficit irrigation experiment. Based on GHGI results (Table 4), The N75–25 and N50-50 were similar ($P > 0.05$), and each one could be selected as the optimum N-fertigation mode. However, the TOPSIS indicated N50-50 as the best option for maximized GY at a minimized GWP (Table 5). Zain et al. (2021) found N25-75 as the best treatment because they only considered yield and its component, factoring out the consequences of the environment especially through GHG emissions. However, our results are consistent with that of Zhang et al. (2021), and suggested that splitting the 240 kg ha^{-1} total N application into 50% basal and 50% topdressing could be the optimal N management mode that balances the wheat yield benefits with the environmental costs of GHG emissions in the NCP.

5. Conclusion

A two-year field experiment was conducted to determine the optimum N-fertigation schedule for winter wheat production in the NCP. The nitrogen scheduling treatments applied in this study significantly ($P < 0.05$) influenced the GHG (CO_2, CH_4 and N_2O) emissions, GWP and grain yield. A significant ($P < 0.01$) correlation was found between N_2O emissions and soil inorganic nitrogen, and the temperature was the major factor affecting CO_2 and CH_4 emission ($P < 0.01$). Excessive application of nitrogen as either basal or topdressing increased the N_2O and CO_2 emissions as well as global warming potential. The N splitting modes under N25–75 and N50-50 respectively reduced global warming potential by an average of 67.68% and 63.48% as compared to the N100-0 pattern. Similarly, compared with N0-100, the N25–75 and N50-50 reduced the global warming potential by an average of 33.57% and 24.95%, respectively. To mitigate global warming potential in winter wheat fields, the rate of basal nitrogen should not exceed 50% of the total 240 kg ha^{-1} N application. For their high yield (9.09 and 8.39 tons ha^{-1}) as well as low GHGI (15.62 and 15.01 kg CO_2 eq. Mg^{-1}), N50–50 or N25-75 could be considered as the best option to sufficiently matched the winter wheat nutrient demand for attaining high yield. Additionally, the TOPSIS analysis confirmed that N50-50 was better than N25-75 N-fertigation mode for high yield and environmental sustainability.

Further studies are necessary to investigate the effects of more precision N-fertigation modes and to determine the optimal N application schedule by including more objectives such as nitrogen use efficiency, plant N uptake, N leaching and yield components in the TOPSIS evaluation.

CRediT authorship contribution statement

Sunusi Amin Abubakar: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Abdoul Kader Mounkaila Hamani:** Investigation, Writing – review & editing. **Jinsai Chen:** Investigation, Writing – review & editing. **Weihao Sun:** Writing – review & editing. **Guangshuai Wang:** Funding acquisition, Methodology, Writing – review & editing. **Yang Gao:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing. **Aiwang Duan:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

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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Appendix A. Supplementary data

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References

Aguilera, E., Guzmán, G., Alonso, A., 2015. Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops. Agron. Sustain. Dev. 35, 713–724. https://doi.org/10.1007/s13593-014-0267-9.

Álvaro-Fuentes, J., Arrúe, J.L., Cantero-Martínez, C., Isla, R., Plaza-Bonilla, D., Quílez, D., 2016. Fertilization scenarios in sprinkler-irrigated corn under Mediterranean conditions: effects on greenhouse gas emissions. Soil Sci. Soc. Am. J. 80, 662–671. https://doi.org/10.2136/sssaj2015.04.0156.

Aronson, E.L., Helliker, B.R., 2010. Methane flux in non-wetland soils in response to nitrogen addition: a meta-analysis. Ecology 91, 3242–3251. https://doi.org/10.1890/09-2185.1.

Aydin, G., Karakurt, I., Aydiner, K., 2012. Analysis and mitigation opportunities of methane emissions from the energy sector. Energy Sources, Part A Recover. Util. Environ. Eff. 34, 967–982. https://doi.org/10.1080/15567031003716725.

Bronson, K.F., Hunsaker, D.J., Williams, C.F., Thorp, K.R., Rockholt, S.M., Del Grosso, S. J., Venterea, R.T., Barnes, E.M., 2018. Nitrogen management affects nitrous oxide emissions under varying cotton irrigation systems in the Desert Southwest, USA. J. Environ. Qual. 47, 70–78. https://doi.org/10.2134/jeq2017.10.0389.

Burton, D.L., Zebarth, B.J., Gillam, K.M., MacLeod, J.A., 2008. Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. Can. J. Soil Sci. 88, 229–239. https://doi.org/10.4141/CJSS06007.

Chen, Z., Chen, F., Zhang, H., Liu, S., 2016. Effects of nitrogen application rates on net annual global warming potential and greenhouse gas intensity in double-rice cropping systems of the Southern China. Environ. Sci. Pollut. Res. 23, 24781–24795. https://doi.org/10.1007/s11356-016-7455-x.

Denmead, O.T., 2008. Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. Plant Soil 309, 5–24. https://doi.org/10.1007/s11104-008-9599-z.

Ding, T., Ning, Y., Zhang, Y., 2017. Estimation of greenhouse gas emissions in China 1990–2013 Tao. Greenh. Gas Sci Technol. 19, 1–19. https://doi.org/10.1002/ghg.1718.

Du, T., Kang, S., Zhang, X., Zhang, J., 2014. China's food security is threatened by the unsustainable use of water resources in North and Northwest China. Food Energy Secur 3, 7–18. https://doi.org/10.1002/fes3.40.

Duan, J., Shao, Y., He, L., Li, X., Hou, G., Li, S., Feng, W., Zhu, Y., Wang, Y., Xie, Y., 2019. Optimizing nitrogen management to achieve high yield, high nitrogen efficiency and low nitrogen emission in winter wheat. Sci. Total Environ. 697, 1–12. https://doi.org/10.1016/j.scitotenv.2019.134088.

Franco-Luesma, S., Cavero, J., Plaza-Bonilla, D., Cantero-Martínez, C., Arrúe, J.L., Álvaro-Fuentes, J., 2020. Tillage and irrigation system effects on soil carbon dioxide (CO_2) and methane (CH_4) emissions in a maize monoculture under Mediterranean conditions. Soil Tillage Res. 196, 1–12. https://doi.org/10.1016/j.still.2019.104488.

Ge, P., Chen, M., Cui, Y., Nie, D., 2021. The research progress of the influence of agricultural activities on atmospheric environment in recent ten years: a review. Atmosphere 12, 1–16. https://doi.org/10.3390/atmos12050635.

Guardia, G., Aguilera, E., Vallejo, A., Sanz-Cobena, A., Alonso-Ayuso, M., Quemada, M., 2019. Effective climate change mitigation through cover cropping and integrated fertilization: a global warming potential assessment from a 10-year field experiment. J. Clean. Prod. 241, 1–12. https://doi.org/10.1016/j.jclepro.2019.118307.

Jamali, M., Soufizadeh, S., Yeganeh, B., Emam, Y., 2021. A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran. Renew. Sustain. Energy Rev. 139, 1–14. https://doi.org/10.1016/j.rser.2021.110704.

Kallenbach, C.M., Rolston, D.E., Horwath, W.R., 2010. Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation. Agric. Ecosyst. Environ. 137, 251–260. https://doi.org/10.1016/j.agee.2010.02.010.

Kostyanovsky, K.I., Huggins, D.R., Stockle, C.O., Morrow, J.G., Madsen, I.J., 2019. Emissions of N_2O and CO_2 following short-term water and n fertilization events in wheat-based cropping systems. Front. Ecol. Evol. 7, 1–10. https://doi.org/10.3389/fevo.2019.00063.

Kumar, D.S., Palanisami, K., 2010. Impact of drip irrigation on farming system: evidence from southern India. Agric. Econ. Res. Rev. 23, 265–272.

Lai, Y.-J., Hwang, C.-L., 1994. Fuzzy multiple objective decision making. In: Fuzzy Multiple Objective Decision Making. Lecture Notes in Economics and Mathematical Systems, vol. 404. Springer, Berlin, Heidelberg, pp. 139–262. https://doi.org/10.1007/978-3-642-57949-3_3.

Li, C., Xiong, Y., Huang, Q., Xu, X., Huang, G., 2020. Impact of irrigation and fertilization regimes on greenhouse gas emissions from soil of mulching cultivated maize (Zea mays L.) field in the upper reaches of Yellow River, China. J. Clean. Prod. 259, 1–15. https://doi.org/10.1016/j.jclepro.2020.120873.

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., da Rosa, E.F.F., van Kessel, C., 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Global Change Biol. 21, 407–417. https://doi.org/10.1111/gcb.12701.

Liu, Z., Zhao, C., Zhao, J., Lai, H., Li, X., 2021. Improved fertiliser management to reduce the greenhouse-gas emissions and ensure yields in a wheat–peanut relay intercropping system in China. Environ. Sci. Pollut. Res. 2, 1–16. https://doi.org/10.1007/s11356-021-17078-1.

Maris, S.C., Teira-Esmatges, M.R., Arbonés, A., Rufat, J., 2015. Effect of irrigation, nitrogen application, and a nitrification inhibitor on nitrous oxide, carbon dioxide and methane emissions from an olive (Olea europaea L.) orchard. Sci. Total Environ. 538, 966–978. https://doi.org/10.1016/j.scitotenv.2015.08.040.

Mehmood, F., 2019. Effect of Different Irrigation Scheduling and Irrigation Methods on Greenhouse Gas Emissions from Winter Wheat Field in the North China Plain. Chinese Academy of Agricultural Sciences.

Mehmood, F., Wang, G., Gao, Y., Liang, Y., Chen, J., Si, Z., Steve, T., Zain, M., 2019. Nitrous oxide emission from winter wheat field as responded to irrigation scheduling and irrigation methods in the North China Plain. Agric. Water Manag. 222, 367–374. https://doi.org/10.1016/j.agwat.2019.06.015.

Mehmood, F., Wang, G., Gao, Y., Liang, Y., Zain, M., Rahman, S.U., Duan, A., 2021. Impacts of irrigation managements on soil CO_2 emission and soil CH_4 uptake of winter wheat field in the North China plain. Water 13, 1–28. https://doi.org/10.3390/w13152052.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., Minami, K., 1996. Nitrous oxide emissions from agricultural fields: assessment, measurement and mitigation. Plant Soil 181, 95–108. https://doi.org/10.1007/BF00011296.

Motavalli, P., 2018. Nitrogen Management Strategies to Improve Corn Growth and Reduce Soil Greenhouse Gas Emissions from Claypan. University of Missouri.

Ning, D., Qin, A., Duan, A., Xiao, J., Zhang, J., Liu, Zhanjun, Liu, Zugui, Zhao, B., Liu, Zhandong, 2019. Deficit irrigation combined with reduced N-fertilizer rate can mitigate the high nitrous oxide emissions from Chinese drip-fertigated maize field. Glob. Ecol. Conserv. 20, 1–12. https://doi.org/10.1016/j.gecco.2019.e00803.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmi, S., 2016. Greenhouse gas emissions from soils—a review. Chem. Erde 76, 327–352. https://doi.org/10.1016/j.chemer.2016.04.002.

Qiu, W., Liu, J., Li, B., Wang, Z., 2020. N_2O and CO_2 emissions from a dryland wheat cropping system with long-term N fertilization and their relationships with soil C, N, and bacterial community. Environ. Sci. Pollut. Res. 27, 8673–8683. https://doi.org/10.1007/s11356-019-07534-4.

Rochette, P., McGinn, S.M., 2005. Methods for measuring soil-surface gas fluxes. In: Soil-Water-Solute Process Characterization. An Integrated Approach. CRC Press, Boca Raton, FL United States, pp. 465–502. https://doi.org/10.1201/9781420032086.ch13.

Schellenberg, D.L., Alsina, M.M., Muhammad, S., Stockert, C.M., Wolff, M.W., Sanden, B. L., Brown, P.H., Smart, D.R., 2012. Yield-scaled global warming potential from N_2O emissions and CH_4 oxidation for almond (Prunus dulcis) irrigated with nitrogen fertilizers on arid land. Agric. Ecosyst. Environ. 155, 7–15. https://doi.org/10.1016/j.agee.2012.03.008.

Si, Z., Zain, M., Li, S., Liu, J., Liang, Y., Gao, Y., Duan, A., 2021. Optimizing nitrogen application for drip-irrigated winter wheat using the DSSAT-CERES-Wheat model. Agric. Water Manag. 244, 1–10. https://doi.org/10.1016/j.agwat.2020.106592.

Si, Z., Zain, M., Mehmood, F., Wang, G., Gao, Y., Duan, A., 2020. Effects of nitrogen application rate and irrigation regime on growth, yield, and water-nitrogen use efficiency of drip-irrigated winter wheat in the North China Plain. Agric. Water Manag. 231, 1–8. https://doi.org/10.1016/j.agwat.2020.106002.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363, 789–813. https://doi.org/10.1098/rstb.2007.2184.

Sun, C., Chen, L., Zhai, L., Liu, H., Wang, K., Jiao, C., Shen, Z., 2020. National assessment of nitrogen fertilizers fate and related environmental impacts of multiple pathways in China. J. Clean. Prod. 277, 1–11. https://doi.org/10.1016/j.jclepro.2020.123519.

Tan, Y., Xu, C., Liu, D., Wu, W., Lal, R., Meng, F., 2017. Effects of optimized N fertilization on greenhouse gas emission and crop production in the North China Plain. Field Crop. Res. 205, 135–146. https://doi.org/10.1016/j.fcr.2017.01.003.

Tian, D., Zhang, Y., Mu, Y., Zhou, Y., Zhang, C., Liu, J., 2017. The effect of drip irrigation and drip fertigation on N_2O and NO emissions, water saving and grain yields in a maize field in the North China Plain. Sci. Total Environ. 575, 1034–1040. https://doi.org/10.1016/j.scitotenv.2016.09.166.

Tong, X., Li, J., Nolan, R.H., Yu, Q., 2017. Biophysical controls of soil respiration in a wheat-maize rotation system in the North China Plain. Agric. For. Meteorol. 246, 231–240. https://doi.org/10.1016/j.agrformet.2017.07.005.

Trost, B., Prochnow, A., Meyer-Aurich, A., Drastig, K., Baumecker, M., Ellmer, F., 2016. Effects of irrigation and nitrogen fertilization on the greenhouse gas emissions of a cropping system on a sandy soil in northeast Germany. Eur. J. Agron. 81, 117–128. https://doi.org/10.1016/j.eja.2016.09.008.

Van der Kooij, S., Zwarteveen, M., Boesveld, H., Kuper, M., 2013. The efficiency of drip irrigation unpacked. Agric. Water Manag. 123, 103–110. https://doi.org/10.1016/j.agwat.2013.03.014.

Wang, G., Liang, Y., Zhang, Q., Jha, S.K., Gao, Y., Shen, X., Sun, J., Duan, A., 2016. Mitigated CH_4 and N_2O emissions and improved irrigation water use efficiency in winter wheat field with surface drip irrigation in the North China Plain. Agric. Water Manag. 163, 403–407. https://doi.org/10.1016/j.agwat.2015.10.012.

Wang, X., Jiang, Y., Jia, B., Wang, F., Zhou, G., 2010. Comparison of soil respiration among three temperate forests in Changbai Mountains, China. Can. J. For. Res. 40, 788–795. https://doi.org/10.1139/X10-010.

Wei, C., Ren, S., Yang, P., Wang, Y., He, X., Xu, Z., Wei, R., Wang, S., Chi, Y., Zhang, M., 2021. Effects of irrigation methods and salinity on CO_2 emissions from farmland soil during growth and fallow periods. Sci. Total Environ. 752, 1–12. https://doi.org/10.1016/j.scitotenv.2020.141639.

Wei, Q., Xu, J., Yang, S., Liao, L., Jin, G., Li, Y., Hameed, F., 2018. Subsurface watering resulted in reduced soil N_2O and CO_2 emissions and their global warming potentials than surface watering. Atmos. Environ. 173, 248–255. https://doi.org/10.1016/j.atmosenv.2017.11.025.

Wu, Jiangqi, Wang, H., Li, G., Wu, Jianghua, Gong, Y., Wei, X., Lu, Y., 2021. Responses of CH4 flux and microbial diversity to changes in rainfall amount and frequencies in a wet meadow in the Tibetan Plateau. Catena 202, 1–12. https://doi.org/10.1016/j.catena.2021.105253.

Zain, M., Si, Z., Li, S., Gao, Y., Mehmood, F., Ur-rahman, S., 2021. The coupled effects of irrigation scheduling and nitrogen fertilization mode on growth, yield and water use efficiency in drip-irrigated winter wheat. Sustainability 13, 1–18. https://doi.org/10.3390/su13052742.

Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X., Jiang, R., 2011. Integrated soil-crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. J. Environ. Qual. 40, 1051–1057. https://doi.org/10.2134/jeq2010.0292.

Zhang, X., Xiao, G., Li, H., Wang, L., Wu, S., Wu, W., Meng, F., 2020. Mitigation of greenhouse gas emissions through optimized irrigation and nitrogen fertilization in intensively managed wheat-maize production. Sci. Rep. 10, 1–10. https://doi.org/10.1038/s41598-020-62434-9.

Zhang, Y., Sheng, J., Wang, Z., Chen, L., Zheng, J., 2015. Nitrous oxide and methane emissions from a Chinese wheat-rice cropping system under different tillage practices during the wheat-growing season. Soil Tillage Res. 146, 261–269. https://doi.org/10.1016/j.still.2014.09.019.

Zhang, Z., Yu, Z., Zhang, Y., Shi, Y., 2021. Finding the fertilization optimization to balance grain yield and soil greenhouse gas emissions under water-saving irrigation. Soil Tillage Res. 214, 1–12. https://doi.org/10.1016/j.still.2021.105167.

Zhou, B., Sun, X., Ding, Z., Ma, W., Zhao, M., 2017. Multisplit nitrogen application via drip irrigation improves maize grain yield and nitrogen use efficiency. Crop Sci. 57, 1687–1703. https://doi.org/10.2135/cropsci2016.07.0623.

Zhong, Y., Li, J., Xiong, H., 2021. Effect of deficit irrigation on soil CO_2 and N_2O emissions and winter wheat yield. J. Clean. Prod. 279, 1–12. https://doi.org/10.1016/j.jclepro.2020.123718.

Zhou, H., Niu, X., Yan, H., Zhao, N., Zhang, F., Wu, L., 2019. Interactive effects of water and fertilizer on yield , soil water and nitrate dynamics of young apple tree in Semiarid region of Northwest China. Agronomy 9, 1–18. https://doi.org/10.3390/agronomy9070360.