Effects of Water-Nitrogen Coupling on NH3 and N2O Emissions from Drip-Irrigated Watermelon in the Hexi Irrigation District (Postprint)

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Abstract

NH3 and N2O emissions are the primary pathways of gaseous nitrogen loss; investigating the effects of different water and nitrogen supply rates on gaseous nitrogen loss under drip irrigation with plastic film is of great significance for formulating water and nitrogen management strategies in watermelon production in the Hexi irrigation district. A split-plot design was adopted in the experiment, with main treatments consisting of three irrigation lower limits set at 80% (I80), 65% (I65), and 50% (I50) of field capacity, the irrigation upper limit set at 95% of field capacity, and subplot treatments comprising four nitrogen application rates of 0 (N0), 100 kg · hm-2 (N100), 200 kg · hm-2 (N200), and 300 kg · hm-2 (N300). Using the aeration method and static chamber-gas chromatography method, the experiment analyzed the dynamic changes in soil NH3 and N2O emissions, as well as watermelon yield and quality under different treatments. The results showed that: (1) Soil gaseous nitrogen emissions were jointly affected by water and nitrogen; NH3 and N2O emissions peaked 1~2 d after basal fertilizer application, lasting for 5~7 d; cumulative emissions were highest during the seedling stage, accounting for 33.33% and 47.22% of the entire growth period, respectively; cumulative NH3 and N2O emissions for the entire growth period were 3.05~15.39 kg hm-2 and 0.51~2.00 kg · hm-2, respectively. (2) Increasing both water and nitrogen supply rates promoted NH3 and N2O emissions, with nitrogen having a greater effect than irrigation; under I80 conditions, increasing nitrogen fertilizer application increased cumulative NH3 and N2O emissions by 63.86%~285.48% and 120.41%~308.82%, respectively. (3) The nitrogen use efficiency (NUE) of treatment I65N200 reached 32.62%, significantly higher than that of treatment I80N300; yield and soluble solids content were 70159 kg hm-2 and 11.39%, respectively, showing no significant difference from treatment I80N300. Considering yield, quality, and nitrogen use efficiency comprehensively, in watermelon cultivation under drip irrigation with plastic film in the Hexi irrigation district, maintaining soil water content between 65%~95% of field capacity and optimizing nitrogen application rate to 200 kg·hm-2 can sustain high yield and quality while facilitating the control of NH3 and N2O emissions.

Full Text

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Key words: watermelon; drip irrigation; water-nitrogen coupling; NH3 emission; N2O emission

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Introduction

China is the world's largest consumer of nitrogen fertilizer, with annual nitrogen application reaching 1745.32$×10^{4}$ tons, accounting for approximately 30%~35% of global consumption—levels below contemporary European and American averages. Following nitrogen application, substantial losses occur through leaching, runoff, and gaseous volatilization, with NH_3 and N_2O representing the primary forms of gaseous nitrogen loss. NH_3 plays a significant role in PM2.5 formation, while N_2O is a major non-CO_2 greenhouse gas and key factor controlling the greenhouse effect. Investigating the quantitative relationship between farmland emissions and water-nitrogen inputs provides a scientific basis for effective nitrogen loss control.

Previous research has established nitrogen application as the primary determinant of nitrogen loss. However, studies examining emission dynamics and regulatory mechanisms driven by irrigation water under drip irrigation conditions in arid regions remain scarce. Therefore, this experiment investigates nitrogen emission characteristics under drip fertigation through a water-nitrogen coupling trial with mulched drip irrigation of watermelon in the Hexi irrigation area, aiming to clarify the quantitative relationship between water-nitrogen supply and nitrogen emissions to support regional water-saving irrigation management strategies.

1.1 Experimental Site Overview

The experiment was conducted at the Zhangye Water Saving Agricultural Experimental Station of the Gansu Academy of Agricultural Sciences (38°85 21 N, 100°38 55 E). The experimental area has an elevation of 1554 m, mean annual temperature of 7.0~7.6 ℃, and annual precipitation of 104~200 mm. The soil is classified as irrigated desert soil, with basic physical and chemical properties presented in . Air temperature and precipitation during the growth period are illustrated in [Figure 1: see original paper].

1.2 Experimental Design

The test cultivar was "Jincheng No. 5" watermelon. The experiment adopted a split-plot design with main plots comprising three irrigation lower limits set at 50%, 65%, and 80% of field capacity (I50, I65, I80), with a uniform upper irrigation limit at 95% of field capacity. Subplot treatments consisted of four nitrogen application rates: 0 $\mathrm{kg \cdot hm^{-2}}$ (N0), 100 $\mathrm{kg \cdot hm^{-2}}$ (N100), 200 $\mathrm{kg \cdot hm^{-2}}$ (N200), and 300 $\mathrm{kg \cdot hm^{-2}}$ (N300), with three replications. Each plot measured 7.5 m in length with a planting density of [value] plants per hectare.

The experiment employed plastic-mulched drip irrigation with drip tape spacing of 50 cm and emitter spacing of 50 cm. Two rows of drip tape were installed under the plastic film. The white polyethylene film (produced by Lanzhou Jintudi Plastic Products Co., Ltd.) had a width of 70 cm and thickness of 0.01 mm. The drip tape (Netafim) had an inner diameter of 16 mm, emitter flow rate of 1.75 $\mathrm{L \cdot h^{-1}}$, and operating pressure of [value]. Watermelon seedlings were transplanted inside the drip tape at a vertical distance of [value] from the emitters.

Irrigation was initiated when the average soil water content in the 0-40 cm profile reached the designated lower limit and continued until the upper limit was achieved. Fertilization was controlled by a proportional fertilizer injector with a fertilizer solution concentration of [value]. Nitrogen was applied as urea (46% N), with 45% applied as base fertilizer and the remainder as topdressing: 20% at vine extension, 20% at fruiting, and 15% at fruit enlargement. Phosphorus (180 $\mathrm{kg \cdot hm^{-2}}$ as calcium superphosphate with 18% P_2O_5) and potassium (75 $\mathrm{kg \cdot hm^{-2}}$ as potassium sulfate with 50% K_2O) were applied as basal fertilizers banded 10 cm below the drip tape.

1.3 Measurements

1.3.1 NH_3 Collection and Determination

NH_3 emission flux was measured using the aeration method. PVC cylinders (15 cm inner diameter, 25 cm height) were used. Phosphoglycerol solution (40 mL glycerol + 40 mL phosphoric acid, diluted to 1000 mL) was used to saturate sponges, which were placed in PVC pipes in two layers: an upper sponge to absorb atmospheric NH_3 and a lower sponge to absorb soil-emitted NH_3.

Collection began on the fertilization day, with aeration devices placed in each plot and samples taken the following morning at 08:00. During sampling, the lower sponge was removed, sealed in a plastic bag, and replaced with a freshly saturated sponge. The upper sponge was replaced every 3-7 days. Collected sponges were placed in 500 mL plastic bottles with 300 mL of $1.0\ \mathrm{mol \cdot L^{-1}}$ KCl solution, oscillated for 30 min, and ammonium concentrations were determined using a SmartChem 140 automatic discrete chemistry analyzer.

1.3.2 N_2O Collection and Determination

N_2O flux was measured using the static chamber method (50 cm × 50 cm × 50 cm). Stainless steel bases were inserted 10 cm into the soil before the experiment, with drip tape passing through the base. During gas sampling, the chamber was placed in a water-filled groove around the base for sealing. Gas samples were collected at 0, 15, and 30 min after chamber closure using a 50 mL syringe for N_2O analysis via gas chromatography (Agilent 7890A). Routine sampling was conducted weekly between 09:00-11:00 Beijing time, with daily sampling after effective precipitation and fertilization events.

1.3.3 Yield and Soluble Solids Content Determination

At harvest, marketable yield was recorded by weighing watermelons from each plot. Simultaneously, three watermelons were randomly selected per plot to determine soluble solids content in the central fruit portion using a handheld refractometer (PLA-1).

1.3.4 Fruit Sample Collection and Total Nitrogen Content Determination

At harvest, three plants were randomly selected per plot. Fruits were chopped, oven-dried at 105 ℃ for 30 min, then at 75 ℃ to constant weight. Dried samples were ground and sieved, with total nitrogen content determined using the Kjeldahl method.

1.4 Calculations

1.4.1 Soil NH_3 Emission Calculation

NH_3 emission flux was calculated as:

$$F_{\mathrm{NH3}} = \frac{C}{A \times t}$$

where F_{NH3} is emission flux ($\mathrm{kg \cdot hm^{-2} \cdot d^{-1}}$), C is measured ammonium nitrogen amount (kg), A is effective sponge area ($\mathrm{hm^2}$), and t is sampling time (d).

Cumulative emissions were calculated as the sum of daily emission fluxes during the measurement period. The NH_3 loss rate was calculated as:

$$\text{Loss rate} = \frac{\text{Cumulative emissions}_{\text{N treatment}} - \text{Cumulative emissions}_{\text{N0 treatment}}}{\text{Total N applied}} \times 100\%$$

1.4.2 Soil N_2O Emission Calculation

N_2O emission flux was calculated as:

$$F_{\mathrm{N2O}} = \frac{\Delta c}{\Delta t} \times \frac{273}{T} \times \frac{P}{1013} \times H \times M \times k$$

where F_{N2O} is emission flux ($\mathrm{g \cdot m^{-2} \cdot h^{-1}}$), $\Delta c / \Delta t$ is concentration change rate ($\mathrm{L \cdot L^{-1} \cdot h^{-1}}$), T is chamber temperature (K), P is atmospheric pressure (hPa), H is chamber height (m), M is N_2O-N molar mass (28 $\mathrm{g \cdot mol^{-1}}$), and k is the unit conversion coefficient (1$×10^{-3}$).

Cumulative emissions were calculated as:

$$T = \sum_{i=1}^{n-1} \left[\frac{F_i + F_{i+1}}{2} \times (t_{i+1} - t_i) \times 24 \times 1 \times 10^{-5} \right]$$

where T is cumulative emission ($\mathrm{kg \cdot hm^{-2}}$), F_i is emission flux at the ith sampling ($\mathrm{g \cdot m^{-2} \cdot h^{-1}}$), and $t_{i+1} - t_i$ is the interval between measurements.

1.4.3 Nitrogen Use Efficiency

Nitrogen use efficiency was calculated as:

$$\text{NUE} = \frac{\text{N uptake}_{\text{N treatment}} - \text{N uptake}_{\text{N0 treatment}}}{\text{Nitrogen applied}} \times 100\%$$

1.5 Data Processing

Data were processed and analyzed using Excel 2019 and SAS 9.4 statistical software. Mean separation was performed using Duncan's multiple range test at P<0.05 significance level.

2 Results

2.1 Effects of Different Treatments on Soil NH_3 Emission Flux

NH_3 emission fluxes were elevated following fertilization, peaking on days 2-5 and gradually decreasing thereafter to minimum values after 7 days. Emission flux was proportional to irrigation and nitrogen application rates, with nitrogen exerting a greater effect than irrigation. As the growth period progressed, emission fluxes declined across all treatments, with fluctuations occurring at topdressing nodes except for treatments I50N0 and I65N0. Under varying irrigation lower limits, average NH_3 emission fluxes during the seedling, vine extension, fruiting, and fruit enlargement stages reached 0.38, 0.60, 0.41, and 0.24 $kg \cdot hm^{-2} \cdot d^{-1}$, respectively, for treatment I80N0, which were significantly higher than those under other irrigation regimes.

2.2 Effects of Different Treatments on Soil NH_3 Cumulative Emissions

Cumulative NH_3 emissions during the entire watermelon growth period ranged from 3.05 to 15.39 $kg \cdot hm^{-2}$, with loss rates of 1.56% to 3.80%. Emissions were concentrated in the seedling stage, accounting for 33.33% of total emissions, followed by the vine extension stage (19.37%), fruiting stage (15.91%), and fruit enlargement stage (6.06%). Both increased irrigation and nitrogen application promoted NH_3 emissions. Raising the irrigation lower limit from 50% to 80% of field capacity increased cumulative emissions by 33.76-41.56% under N0, 50.87-79.16% under N100, and 67.83-96.19% under N200. The effect of nitrogen exceeded that of irrigation, with cumulative emissions increasing by 63.91-285.71% when nitrogen application increased under the same irrigation condition. Treatment I80N300 exhibited the highest cumulative emissions and loss rate at 15.39 $kg \cdot hm^{-2}$ and 3.80%, respectively.

Detailed cumulative emissions and loss rates for each treatment are presented in .

2.3 Effects of Different Treatments on Soil N_2O Emission Flux

Both irrigation and nitrogen application significantly affected soil N_2O emission flux. Emissions peaked 1-2 days after fertilization, decreased markedly after 4-5 days, and returned to baseline levels. Base fertilizer, vine fertilizer, fruit fertilizer, and enlargement fertilizer accounted for 45%, 20%, 20%, and 15% of total nitrogen application, respectively. Peak emission fluxes during each period were 269.84, 238.58, 716.14, and 359.55 $g \cdot m^{-2} \cdot h^{-1}$, respectively. Increasing nitrogen application enhanced N_2O emission flux by 176.19-492.65% during the seedling stage, 180.69-559.11% during the vine extension stage, and 89.78-379.17% during the fruiting stage. High water and high nitrogen conditions, particularly treatment I80N300, promoted the highest N_2O emission flux at 716.14 $g \cdot m^{-2} \cdot h^{-1}$.

2.4 Effects of Different Treatments on Soil N_2O Cumulative Emissions

Cumulative N_2O emissions during the watermelon growth period ranged from 0.51 to 2.00 $kg \cdot hm^{-2}$. Emissions were concentrated in the seedling stage, accounting for 47.22% of total emissions, with the vine extension stage contributing the least at 15.91%, followed by the fruiting stage at 17.52%. Irrigation increased cumulative N_2O emissions by 13.51-26.67%, with significant promotion during the vine extension stage ($F=17.90$, $P<0.05$). Nitrogen application had significant effects throughout the growth period, increasing cumulative emissions by 120.41-308.82% under I80 conditions. The effect of nitrogen exceeded that of irrigation, and the coupling effect was not significant. Treatment

I80N300 showed the highest cumulative emissions at 2.00 $kg \cdot hm^{-2}$.

Detailed cumulative N_2O emissions for each treatment are presented in .

2.5 Effects of Different Water-Nitrogen Treatments on Watermelon Yield and Soluble Solids Content

Irrigation had highly significant effects on marketable watermelon yield and nitrogen uptake, and significant effects on soluble solids content. Nitrogen application had highly significant effects on yield, nitrogen uptake, and soluble solids content. The interaction between irrigation and nitrogen had significant effects on yield and nitrogen uptake, but not on soluble solids content.

Under the same irrigation treatment, increasing nitrogen application initially increased yield then decreased it after reaching a maximum. Yield and soluble solids content were highest in treatments I80N300 and I65N200, with no significant difference between them. Nitrogen application significantly increased plant nitrogen uptake. Under the same irrigation lower limit, treatments N200 and N300 increased nitrogen uptake by 46.92-65.20% and 59.94-83.02% compared to N100, respectively. However, nitrogen use efficiency decreased with higher nitrogen rates. Treatment I65N200 achieved the highest nitrogen use efficiency at 32.62%, significantly higher than I80N300, while maintaining relatively high yield and soluble solids content at 70159 $kg \cdot hm^{-2}$ and 11.39%, respectively, which were not significantly different from I80N300.

Detailed yield, quality, and nitrogen absorption data are presented in .

3 Discussion

3.1 Effects of Different Water-Nitrogen Treatments on Soil NH_3 Emission Characteristics

NH_3 emissions are jointly affected by irrigation and nitrogen application. Nitrogen provides the material basis for emissions, as urea decomposes rapidly through urease action after application. Water influences NH_3 emissions through evaporation transport and participation in hydrolysis reactions. Unlike flood irrigation, drip irrigation results in slower soil moisture changes and weaker water vapor diffusion, making it difficult to provide sufficient conditions for NH_3 emissions. Consequently, nitrogen plays a more significant role in NH_3 emissions under drip irrigation.

Results showed that nitrogen-induced emission peaks were more pronounced than irrigation effects. Under the same nitrogen rate, increasing the irrigation lower limit from 50% to 80% of field capacity increased cumulative NH_3 emissions by 16.30-43.94%. Under the same irrigation condition, increasing nitrogen application increased cumulative emissions by 46.28-74.96%. The effect of nitrogen was greater than irrigation, consistent with findings from other crops. In production practice, reducing nitrogen application is often the first consideration for decreasing NH_3 emissions, though water management should also be considered. Drip irrigation is an effective measure for reducing NH_3 volatilization losses.

3.2 Effects of Different Water-Nitrogen Treatments on Soil N_2O Emission Characteristics

Both nitrification and denitrification processes in soil produce N_2O. Soil moisture content at 65%-95% of field capacity promotes nitrification, while higher moisture levels deteriorate aeration conditions and may reduce emissions. However, this study found that N_2O emission flux still increased by 2.78-26.67% when irrigation increased, with the maximum emission flux occurring in treatment I80N300. The region experiences strong soil evaporation, and the rhizosphere environment created by drip irrigation undergoes rapid changes, providing conditions for both nitrifying and denitrifying bacteria to coexist and continuously release N_2O.

Increasing water and nitrogen inputs promoted N_2O cumulative emissions, particularly under high soil moisture conditions with high nitrogen application. The effect of nitrogen was greater than irrigation, likely because nitrogen addition provides more substrate for nitrification and denitrification processes. Drip fertigation creates temporary anaerobic conditions, and the lack of N_2O reductase genes in ammonia-oxidizing bacteria leads to N_2O as the final product. This result aligns with previous research, confirming drip irrigation as a feasible emission reduction measure.

3.3 Effects of Different Water-Nitrogen Treatments on Watermelon Yield and Quality

Moderate reduction in water and fertilizer application can stabilize yield and improve quality while achieving high nitrogen use efficiency and effectively reducing emissions. Yield and nutrient use efficiency improvements occur because drip irrigation concentrates fertilizers in the root zone, while plastic mulching increases soil temperature and accelerates nutrient diffusion, enhancing nutrient absorption efficiency. Reduced water application improves quality by decreasing dilution of soluble solids and increasing soluble acid invertase activity under water deficit conditions, thereby increasing soluble sugar content.

This study found that appropriate water-nitrogen levels (I65N200) met watermelon nitrogen demand, achieved high yield and quality through water-fertilizer regulation, and effectively controlled gaseous nitrogen losses from an input perspective, improving nitrogen use efficiency and achieving coordination between appropriate water management and ecological environment. Treatment I65N200 achieved 32.62% nitrogen use efficiency, significantly higher than high water-high nitrogen treatments, with yield and soluble solids content not significantly different from I80N300. This treatment effectively controlled NH_3 and N_2O emissions while maintaining high yield and quality, representing an optimal water-nitrogen management strategy for watermelon production under plastic-mulched drip irrigation in the Hexi irrigation area.

4 Conclusion

1. Soil nitrogen gas emissions from plastic-mulched drip-irrigated watermelon fields are jointly affected by irrigation and nitrogen application. NH_3 emission flux peaked 1-2 days after base fertilizer application and decreased to minimum values after 5-7 days. Cumulative NH_3 emissions during the growth period ranged from 3.05 to 15.39 $kg \cdot hm^{-2}$, with loss rates of 1.56% to 3.80%. Soils with higher moisture content promoted NH_3 emissions, with cumulative emissions increasing by 63.91-285.71% when nitrogen application increased under I80 conditions.

2. N_2O emission flux peaked 1-2 days after nitrogen application, decreased significantly after 4-5 days, and returned to baseline levels. Peak emissions occurred after base fertilizer application, reaching 716.14 $g \cdot m^{-2} \cdot h^{-1}$. Cumulative N_2O emissions ranged from 0.51 to 2.00 $kg \cdot hm^{-2}$, concentrated in the seedling stage (47.22% of total). Increased water-nitrogen inputs enhanced N_2O emissions by 120.41-308.82%. Both irrigation and nitrogen had highly significant effects on N_2O emissions throughout the growth period.

3. Considering yield, quality, and nitrogen utilization comprehensively, treatment I65N200 (irrigation lower limit at 65% field capacity, nitrogen rate at 200 $kg \cdot hm^{-2}$) achieved 32.62% nitrogen use efficiency with yield and soluble solids content of 70159 $kg \cdot hm^{-2}$ and 11.39%, respectively, not significantly different from I80N300. This treatment effectively controlled NH_3 and N_2O emissions while maintaining high yield and quality, representing the optimal water-nitrogen management strategy for watermelon production under plastic-mulched drip irrigation in the Hexi irrigation area.

Note: Figure translations are in progress. See original paper for figures.

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