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RESEARCH ARTICLE

Quantitative assessment of nitrogen fertilizer losses with nitrification inhibitors and urease inhibitors

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Against the backdrop of excessive global nitrogen fertilizer use, the loss of nitrogen fertilizer has led to environmental pollution and resource waste. Therefore, finding effective mitigation measures is of great significance for sustainable agricultural development. This study examined the problems of nitrogen fertilizer loss in soil and the potentials of nitrification inhibitors and urease inhibitors to reduce it by using quantitative analysis methods. Different soil types and treatment areas at the ecological agriculture experimental station were included in the study with different ratios of nitrification inhibitor, 3,4-Dimethylpyrazole phosphate (DMPP), and urease inhibitor, N- (n-butyl) thiophosphoric triamide (NBPT) treatments. The indicators for the degree of nitrogen fertilizer loss measurement included ammonia volatilization, nitrogen leaching, and nitrogen fertilizer utilization efficiency. The results showed that, by using the $CO(NH_2)_2$+DMPP+NBPT treatment method, the cumulative losses of ammonia volatilization in sandy soil and clay soil after 15 days were 5,430.36 g N/hm^2 and 4,130.36 g N/hm^2, respectively. The nitrogen runoff loss rates were approximately 36-60% and 34-45%, respectively. The nitrogen leaching loss rates were about 20-74% and 15-50%, respectively. The nitrogen fertilizer utilization efficiency for wheat was approximately 36.1-37.4% and 44.3-45.6%, respectively. The results indicated that the utilization of nitrification/urease inhibitors could significantly reduce nitrogen fertilizer loss and improve its overall utilization efficiency. The results of this study offered valuable insights for enhancing environmental conservation and promoting food security.

Keywords: nitrification inhibitor; urease inhibitor; nitrogen fertilizer loss; soil; agriculture; environment; ecological agriculture.

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Introduction

With the development of agricultural production, the widespread application of nitrogen fertilizer has become one of the key measures to improve crop yield and ensure food security. However, excessive use of nitrogen fertilizer has resulted in serious nitrogen fertilizer losses, leading to resource waste and environmental consequences like groundwater and water pollution, as well as greenhouse gas emissions [1-3]. To reduce nitrogen fertilizer loss and improve nitrogen fertilizer utilization efficiency, many studies have been conducted on general nitrogen fertilizer loss. Yang *et al*. designed five planting modes of slope field experiments to investigate the control effect of soil erosion on slopes that caused nitrogen and phosphorus losses. The results showed that compared to the traditional planting mode, the runoff nitrogen loss load of other four planting modes decreased by 52.8%, 56.8%, 46.1%, and 50.2%, respectively [4]. Zheng *et al*. conducted 28 rainfall observations on three different vegetation cover lands to address the issue of soil nitrogen loss caused by surface and groundwater flows. The data on the total nitrogen loss caused by surface runoff, inter runoff, and groundwater runoff were recorded, and the results indicated that grassland coverage had a high retention of nitrogen runoff loss, while litter coverage led to increased nitrogen leaching [5]. Gu *et al*. investigated the nitrogen and phosphorus levels for the highest yield of grass under mulching and the mechanism of yield decline under high nitrogen and phosphorus levels. A 6-year study was conducted by using random plot segmentation design experiments with and without plastic film coverage. The results indicated that in the semi-arid Loess Plateau, the grass yield with coverage, phosphorus retention, and low risk of nitrogen loss was the highest [6]. Zhu *et al*. conducted a study on the spatiotemporal distribution of anaerobic ammonia oxidizing bacteria and nitrosamobacteria in soil profiles to utilize the effects of anaerobic ammonia oxidation and anaerobic methane oxidation in agricultural dryland soils with isotope tracing technology to monitor nitrogen conversion activity in soil for one year. The results showed that anaerobic ammonia oxidation with 1.0% nitrogen loss in winter and 14.4% nitrogen loss in summer and nitrogen denitrifying anaerobic methane oxidation (DAMO) with 0.6% nitrogen loss in winter dominated in surface soil [7]. Che *et al*. investigated the impact of degraded patches' formation on soil properties and nitrogen-cycling microbes (NCMs) in three alpine meadows at varying stages of degradation. The results showed that most soil nutrients including carbon, nitrogen, and phosphorus in the degraded patches were significantly reduced compared to the original grassland patches. The δ N-15 value and nitrate content of soil with degraded patches also tended to be higher [8].

Various measures have been proposed to address nitrogen fertilizer loss including the use of nitrification and urease inhibitors. Nitrification inhibitors can inhibit the activity of ammonia oxidizing bacteria, thereby reducing the rate of nitrogen conversion to nitrate and delaying nitrate leaching and loss. Urease inhibitors can inhibit the activity of urease, prevent urea from decomposing into ammonia nitrogen, reduce ammonia volatilization and nitrogen loss [9, 10]. Many extensive studies on the effects of nitrification/urease inhibitors have been conducted. Tao *et al*. studied the effects of nitrification/urease inhibitors on soil N_2O emissions under drip irrigation systems in both pot and field experiments. The results showed that on the 14th and 35th days of the pot experiment, adding inhibitors reduced nitrogen loss by 7.39% and 7.44%, respectively. In the field experiment, the addition of inhibitors resulted in a decrease of nitrogen loss by 10.53% and 6.65% during two growth stages of wheat [11]. Luchibia *et al*. established incubation experiments to determine the effects of 3,4-Dimethylpyrazole phosphate (DMPP), a nitrification inhibitor, and N- (n-butyl) thiophosphoric triamide (NBPT), a urease inhibitor on the abundance and community composition of urea decomposing and nitrifying microorganisms in selected agricultural soils in Australia. Urea, urea + NBPT, urea + DMPP, and urea + NBPT + DMPP experiments were applied to soil cultivated at 25°C and 60% water filled pore space for 28 days before the concentrations of ammonia and nitrate were measured. The results demonstrated that NBPT and DMPP could reduce nitrogen loss and improve nitrogen fertilizer efficiency by directly inhibiting the growth of ammonia-oxidizing bacteria (AOB) and complete ammonia oxidizers (comammox Nitrospira) in soil [12]. In addition, Karydogianni *et al*. studied the effects of different combinations of urea and inhibitors on cotton yield and fiber traits by using nitrogen indicators to assess these combinations. The results showed that the combination of urease inhibitor and nitrification inhibitor could achieve higher yield and the best fiber quality [13]. Muneer *et al*. investigated the effects of NBPT and NBPT + dicyandiamide (DCD) combined with urea on the volatilization of NH_3 in different soils under different environmental conditions at three field experimental sites. The results showed that NBPT and NBPT + DCD significantly reduced NH_3 volatilization by 80-93% and 75-

90%, respectively. The improvement of urea by NBPT and NBPT + DCD had the potential to slow down soil NH_3 volatilization [14].

Nitrification/urease inhibitors have a certain effect on reducing soil nitrogen fertilizer loss, but there are also some controversies, mainly caused by differences in experimental conditions, sample size limitations, data analysis methods, testability issues, and a lack of long-term research, as well as a lack of quantitative analysis study. Therefore, this study focused on the quantitative analysis of the impact of nitrification and urease inhibitors on nitrogen fertilizer loss by using both laboratory and field experimental data, as well as combining experimental simulation and statistical analysis methods to systematically evaluate the reduction effect of nitrification inhibitors and urease inhibitors on soil nitrogen loss. The results of this study would improve the accuracy of nitrogen fertilizer loss assessment and provide reasonable nitrogen fertilizer management strategies for agricultural production.

Materials and Methods

Analysis of nitrogen fertilizer loss factors and nitrification/urease inhibitors

Three pathways for losing nitrogen fertilizer along with the mechanisms of nitrification inhibitor DMPP/urease inhibitor NBPT were analyzed. The three main pathways for nitrogen loss in soil were soil nitrogen leaching loss, soil nitrogen runoff loss, and diffusion into the atmosphere through gaseous means. There are many factors that affect nitrogen fertilizer leaching loss and runoff loss including the erosion effect of rainfall or irrigation water, especially heavy rainfall or excessive irrigation water, and soil properties such as soil permeability and water retention capacity. Differences in soil types may result in varying losses of nitrogen fertilizer due to leaching and runoff. Meanwhile, improper use of fertilization methods and amounts is also one of the reasons for losses such as unreasonable selection of fertilization time, high fertilization concentration, or excessive use. In addition, the control of fertilization time during crop growth can also have an impact on leaching loss and runoff loss. Further, environmental factors should be considered as the loss of nitrogen fertilizer into water bodies may cause eutrophication and pose a risk of water pollution. Ammonia volatilization is the main pathway for soil gaseous loss. Denitrifying bacteria can reduce nitrate and nitrite to N_2 or release nitrogen oxides into the atmosphere [15, 16]. The highest proportion in the global synthetic nitrogen fertilizer market is urea, at approximately 55%. Urea is a frequently utilized nitrogen fertilizer in agriculture. The mechanism of the conversion of urea into ammonium nitrogen is shown in equation (1).

$$\begin{cases} \{CO(NH_2)_2 \xrightarrow{urase} \left(NH_4\right)_2 CO_3 \\ \left(NH_4\right)_2 CO_3 \to CO_2 + \left(NH_4^+ - N\right) \end{cases} \tag{1}$$

Urinary enzyme inhibitors can decelerate the conversion of urea into ammonium nitrogen by safeguarding urea molecules, decreasing their solubility, and impeding the physiological metabolism of urease-producing organisms. Additionally, these inhibitors reduce urease activity, ultimately minimizing ammonia volatilization loss. There are many types of urease inhibitors, and in this study, the NBPT urease inhibitor, which is widely used and widely recognized as having the most significant inhibitory effect, was selected as the research object. The ammonia generated by the decomposition of urea after entering the soil is the product of nitrification reaction, which is mainly divided into two steps. The first step process is shown in equation (2).

$$NH_3 + O_2 + 2H^+ + 2e^- \to NO_2^- + 5H^+ + 4e^- \tag{2}$$

The process in equation (2) will produce the intermediate product NH_2OH, which can further generate greenhouse gases. The second step process is shown in equation (3).

$$NO_2^- + \frac{1}{2} \rightarrow NO_3^- \tag{3}$$

The bacteria involved in the process of equation (3) are nitrifying bacteria, and if either step of these two reactions is inhibited, the entire nitrification reaction will be inhibited. The principle of nitrification inhibitors is to slow down the nitrification reaction by obstructing the ammonia oxidation process in nitrification. This effect is mainly achieved by affecting the activity of ammonia oxidizing bacteria (AOB and AOA). There are many types of nitrification inhibitors. This study has chosen DCD and DMPP nitrification inhibitors that have received extensive commercial utilization as the objects of research.

Evaluation indicators and methods for nitrogen fertilizer losses

Indicators for assessing nitrogen fertilizer losses were identified, and a simulated field experiment to evaluate different soil and inhibitor ratios was designed. The inhibitory effects of urease/nitrification inhibitors in different land types and ecosystems are related to the type of inhibitor ratio, soil pH, rainfall in the environment, and irrigation. The experimental site was selected at the ecological agriculture experimental station. The climate in this region is mild with an average annual temperature of 18.9°C and an average precipitation of 799 mm. The test soil was selected from sandy soil and clay soil within the ecological experimental area, and the basic physical and chemical properties of different types of soil in the experimental area were treated to be consistent with the surface soil of common crops in the local area as pH 7.34, organic matter 34.5 g/kg, total nitrogen 2.11 g/kg, total phosphorus 1.02 g/kg, and cation exchange rate 18.1 cmol/kg. The common crop wheat was selected as the test crop. The nitrogen losses were tested by using urea with a nitrogen content of 46.0% and NBPT (BASF Chemical Company, Shanghai, China) and DMPP (Dow Chemical Company, Wilmington, DE, USA), respectively, acting as the urease and nitrification inhibitors. 10 sets of 3 × 3 m^2 treatment zones were set up in the experimental area with 3 repeats in each treatment zone, and each treatment zone was isolated with isolation plates. 5 groups of sandy soil and clay soil tests were set up with equal amounts of water, $CO(NH_2)_2$, $CO(NH_2)_2$ + NBPT, $CO(NH_2)_2$ + DMPP, $CO(NH_2)_2$ + DMPP + NBPT, and were irrigated for 30 days, respectively. The amount of $CO(NH_2)_2$ used in each treatment area was set to 100 kg/hm^2 with an N_2 content of 50 kgN/hm^2, while the amounts of DMPP and NBPT were 1% and 0.5% of the N_2 content, respectively. This study selected nitrogen leaching, ammonia volatilization, and nitrogen losses utilization rate as indicators for evaluating nitrogen loss.

(1) Determination of ammonia volatilization in soil

The study used the "aeration method" to determine soil ammonia volatilization. The "aeration method" measured ammonia volatilization in PVC pipes with two layers of sponges that served as porous absorption media for ammonia gas, and each layer needed to be evenly soaked in 30 mL of glycerol phosphate solution to fully absorb it. The upper layer sponge prevented the entry of ammonia and impurities from the air into the PVC pipe, while the lower layer sponge absorbed volatile ammonia in the soil. After applying nitrogen fertilizer to the wheat in each treatment area, the lower layer sponge was replaced every day to measure the rate of ammonia volatilization in the soil, repeating for 15 days. The replaced sponges were stored in a refrigerator at 4°C before measurement. When measuring soil ammonia volatilization, a sponge that had absorbed ammonia gas was put in a 1 L beaker and 500 mL of 0.5 mol/L potassium sulfate solution was added. The beaker was shaken at 150 rpm for 2 hours to extract NH_4^+- N from the solution. The extract was then analyzed by using a continuous flow injection analyzer to determine the concentration of NH_4^+- N [17]. The calculation formula for ammonia volatilization rate is shown in equation (4).

$$v_{(NH_3)} = \frac{A}{B*C} \times 10^{-2} \tag{4}$$

where $v_{(NH_3)}$ was the ammonia volatilization rate. A was the measured NH_4^+-N concentration. B was the cross-sectional area of the PVC pipe. C was the interval time. The cumulative loss $M_{(NH_3)}$ of ammonia volatilization in one day was shown in equation (5).

$$M_{(NH_3)} = m_1 - m_0 \tag{5}$$

where m_1 was the daily ammonia absorption amount of the sponge in the lower layer of each fertilization treatment area. m_0 was the daily ammonia absorption amount of the lower layer sponge in the control group. By using ^{15}N labeled nitrogen losses, the nitrogen utilization efficiency $^{15}N_{\text{rec}}$ could be obtained as shown in equation (6).

$$^{15}N_{\text{rec}} = \frac{F_{sample} - F_{ref}}{F_{tracer} - F_{ref}} \times \frac{N_{pool}}{N_{tracer}} \tag{6}$$

where F_{sample} represented the percentage of ^{15}N atoms in the labeled sample. F_{ref} was the percentage of ^{15}N atoms in unlabeled samples. F_{tracer} was tracer atomic percentage. N_{pool} was the nitrogen mass of the soil reservoir. N_{tracer} was the mass of nitrogen applied.

(2) Determination of soil leaching loss, runoff loss, and nitrogen losses utilization efficiency of wheat

For the leaching loss and runoff loss of nitrogen, the "wheat soil planting system" designed by Alcantud was adopted [18]. The artificial simulation of rainfall in this system was achieved by using a sprinkler automatic rainfall device. Local historical rainfall data was used to determine rainfall frequency and intensity [19]. The study established artificial rainfall every 7 days with an intensity of 30 mm/h and a duration of 1 hour. The process was repeated 6 times. The calculation method for surface runoff and soil leaching water, runoff, and sediment in each treatment area after simulating rainfall was shown in equation (7).

$$R = R_t - \frac{W_S}{r_s} - \frac{W_S}{r_o} \tag{7}$$

where R was the runoff on the slope. R_t was the muddy water runoff. W_s was the amount of eroded sediment. r_s was the relative density of the slope soil. r_o was the water density. e was the soil porosity. The average sediment concentration S of slope runoff was shown in equation (8).

$$S = \frac{r_s w_s}{r_s R_1 - W_s\left(1 + r_s - r\right)} \tag{8}$$

500 mL of collected 5 sets of runoff and leaching water samples were taken for experimental detection. After the entire experiment, 10 wheat plants with uniform growth were selected from each treatment area for nitrogen content detection. The alkaline persulfuric acid clock digestion UV spectrophotometry was used to detect total nitrogen in water samples, while UV spectrophotometry was used to detect nitrate nitrogen in water samples, and Nessler's reagent spectrophotometry was used to detect ammonia nitrogen in water samples. A nitrogen analyzer was used to detect the total nitrogen content of plants. The calculation method for the total nitrogen loss $m_{\text{Total nitrogen}}$ of the entire system on the ground of various detection indicators was shown in equation (9).

$$m_{\text{Total nitrogen}} = m_{\text{Nitrogen leaching}} + m_{\text{Ammonia volatiliz ation}} + m_{\text{Nitrogen runoff loss}} \tag{9}$$

where $m_{\text{Nitrogen leaching}}$ was the nitrogen leaching loss content; $m_{\text{Ammonia volatiliz ation}}$ was the ammonia volatilization content. $m_{\text{Ammonia volatiliz ation}}$ represented the runoff content. The calculation method for the relative loss rate $\eta_{(\text{Total nitrogen loss})}$ of total nitrogen was shown in equation (10).

$$\eta_{(\text{Total nitrogen loss})} = \frac{D_1 - D_0}{D_0} \times 100\% \tag{10}$$

where D_1 was the total nitrogen content of the treatment zone. D_0 was the total nitrogen content of the control group. The calculation method for nitrate nitrogen leaching $\eta_{\text{Nitrate nitrogen}}$ was shown in equation (11).

$$\eta_{\text{Nitrate nitrogen}} = (CN) \times V_a / A_a \tag{11}$$

where CN was the nitrate nitrogen content in the lost water. V_a was the volume of fluid loss. A_a was the soil area. The calculation method for nitrogen accumulation N_{Wheat} in wheat plants was shown in equation (12).

$$N_{\text{Wheat}} = m_{\text{Plant dry matter}} \times m_{\text{Nitrogen content of plants}} \tag{12}$$

where $m_{\text{Plant dry matter}}$ was the dry matter yield of wheat. $m_{\text{Nitrogen content of plants}}$ was the nitrogen content of wheat plants. The calculation method for negative nitrogen balance $N_{\text{Negative nitrogen balance}}$ of plants was shown in equation (13).

$$N_{\text{Negative nitrogen balance}} = N_1 - N \tag{13}$$

where N_1 represented the nitrogen accumulation of wheat plants in the treatment area. N was the amount of nitrogen losses applied. The calculation method for nitrogen losses utilization rate $\eta_{(\text{Nitrogen utilizatio n rate})}$ was shown in equation (14).

$$\eta_{(\text{Nitrogen utilizatio n rate})} = \frac{N_1 - N_0}{m_{\text{Nitrogenou s fertilizer}}} \times 100\% \tag{14}$$

where N_1 represented the nitrogen accumulation of wheat plants in the treatment area. N_0 represented the nitrogen accumulation of wheat plants in the control group. $m_{(\text{Nitrogenou s fertilizer})}$ was the amount of nitrogen losses used in the treatment area.

Statistical analysis

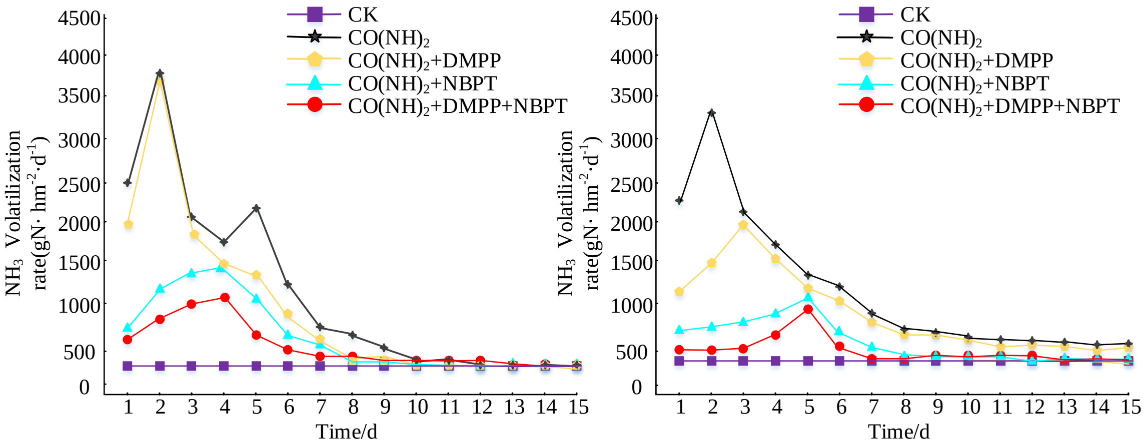
All experimental results were statistically analyzed by using Microsoft Excel (Microsoft, Redmond, WA, USA) and OriginPro 8.0 (OriginLab, Northampton, MA, USA).

Results and discussion

Nitrogen fertilizer is an important agricultural resource widely used in agricultural production. However, improper use and management of nitrogen fertilizer often leads to a significant loss of nitrogen fertilizer, which has a negative impact on the environment and sustainable agricultural development. Therefore, it is very important to evaluate nitrogen fertilizer losses and study the effectiveness of loss reduction techniques.

Analysis of soil ammonia volatilization rate under different fertilization schemes

The ammonia volatilization rate, ammonia volatilization cumulative loss, nitrogen runoff loss rate, nitrogen leaching loss rate, and nitrogen utilization rate in soil were analyzed and discussed in sequence. The ammonia volatilization rates of $CO(NH_2)_2$ combined with NBPT/DMPP treatment under two soil conditions were shown in Figure 1. The characteristics of ammonia volatilization rate in sandy soil treated with $CO(NH_2)_2$ combined with different inhibitors showed that, on the second day after fertilization, the single $CO(NH_2)_2$ treatment and $CO(NH_2)_2$ + DMPP treatment reached the maximum ammonia volatilization rate as 3,861.23 $gN/hm^2 \cdot d$ and 3,813.41 $gN/hm^2 \cdot d$, respectively. The ammonia volatilization rate of single $CO(NH_2)_2$ treatment showed a small peak in 5 days, then gradually decreased, and entered a slow volatilization state after the 10th day. Both



(a)Sandy soil

(b)Clay soil

Figure 1. Ammonia volatilization rate under different fertilization ratios in two types of soil. CK: control group.

$CO(NH_2)_2$ + NBPT and $CO(NH_2)_2$ + DMPP + NBPT treatments reached the peak of ammonia volatilization rate on the 5th day as 1,406.98 gN/hm^2·d and 1,035.78 gN/hm^2·d, respectively. After the 8th day, the rate began to stabilize and entered a slow-release state (Figure 1a). The characteristics of ammonia volatilization rate in clay soil treated with $CO(NH_2)_2$ in combination with different inhibitors demonstrated that the single $CO(NH_2)_2$ treatment reached a peak ammonia volatilization rate of 3,361.75 gN/hm^2·d on the second day, and the $CO(NH_2)_2$ + DMPP treatment reached a peak of 2,011.36 gN/hm^2·d on the third day. These two treatments gradually stabilized and entered a slow volatilization state after the 10th day. Both $CO(NH_2)_2$ + NBPT treatment and $CO(NH_2)_2$ + DMPP + NBPT treatment reached the peak of ammonia volatilization rate on the 5th day as 1,066.25 gN/hm^2·d and 893.25 gN/hm^2·d, respectively. After the 8th day, they began to stabilize and entered a slow release state (Figure 1b). The results indicated that different inhibitors combined with $CO(NH_2)_2$ treatment had different effects on the ammonia volatilization rate in sandy soil and clay soil. $CO(NH_2)_2$ + DMPP + NBPT could effectively delay the ammonia volatilization rate and reduce the peak value of ammonia volatilization in different soil types, thereby effectively reducing the loss of nitrogen fertilizer in the soil.

Analysis of soil ammonia volatilization cumulative loss under different fertilization schemes

The study analyzed the cumulative loss of ammonia volatilization caused by the combination of urea with NBPT/DMPP treatment in two soil conditions. The results demonstrated that variation characteristics of ammonia volatilization accumulation loss in sandy soil treated with $CO(NH_2)_2$, $CO(NH_2)_2$ + DMPP, $CO(NH_2)_2$ + NBPT, and $CO(NH_2)_2$ + DMPP + NBPT on the 15th day were 14,012.36 gN/hm^2, 12,963.41 gN/hm^2, 7,323.19 gN/hm^2, and 5,430.36 gN/hm^2, respectively (Figure 2a). The cumulative losses of ammonia volatilization in $CO(NH_2)_2$ and $CO(NH_2)_2$ + DMPP treatments were mainly concentrated in the first 8 days with a fast growth rate. The cumulative losses of ammonia volatilization in $CO(NH_2)_2$ + NBPT, $CO(NH_2)_2$ + DMPP + NBPT treatments were mainly concentrated in the first 5 days with a relatively slow growth rate. Figure 2b showed the variation characteristics of ammonia volatilization accumulation loss in clay soil under the treatments of $CO(NH_2)_2$ combined with different inhibitors with $CO(NH_2)_2$, $CO(NH_2)_2$ + DMPP, $CO(NH_2)_2$ + NBPT, and $CO(NH_2)_2$ + DMPP + NBPT on the 15th day as 11,836.89 gN/hm^2, 11,252.42 gN/hm^2, 6,223.19 gN/hm^2, and 4,130.36 gN/hm^2, respectively. The results showed that, under different inhibitor treatments, the volatilization

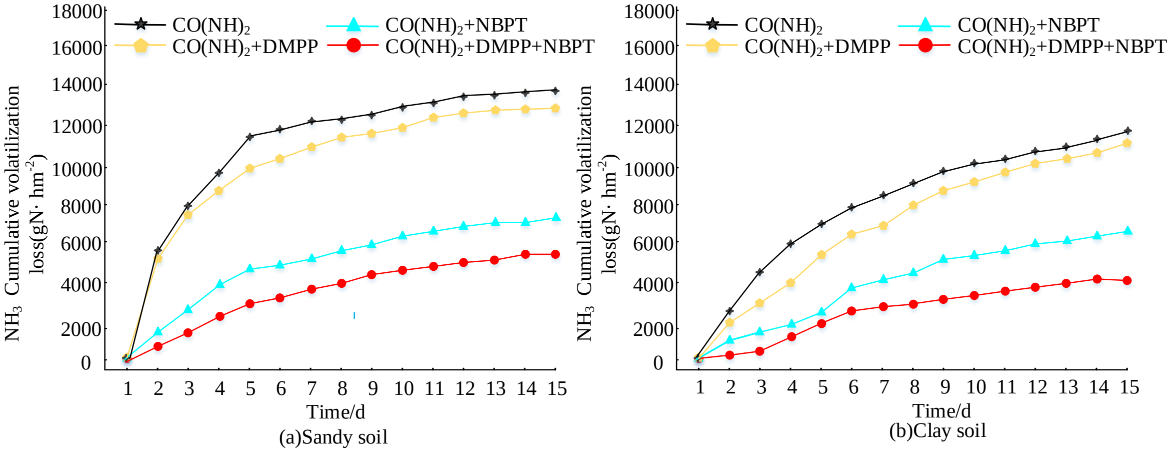


Figure 2. Accumulative loss of ammonia volatilization under different fertilization ratios in two types of soil.

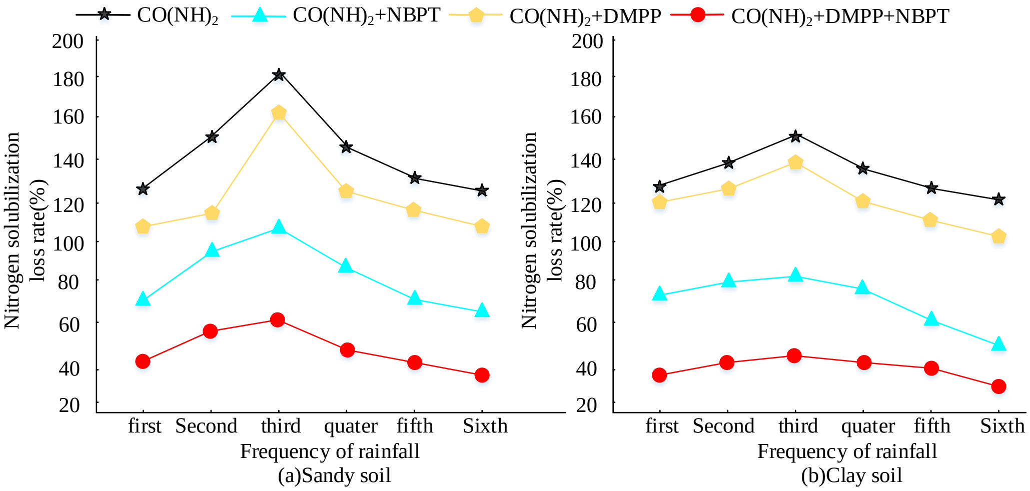
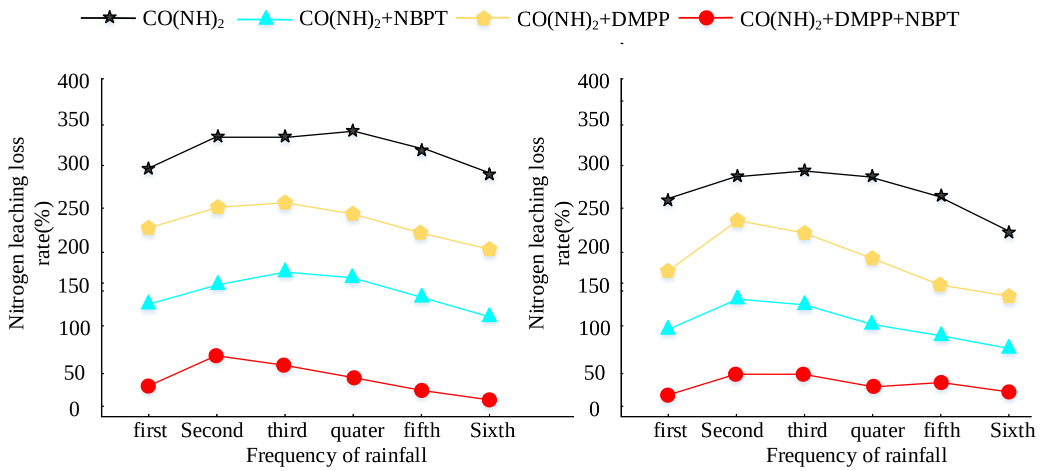


Figure 3. Nitrogen runoff rate under different fertilization ratios in two types of soil.

and accumulation losses of ammonia in sand and clay treated with $CO(NH_2)_2$ exhibited different characteristics of variation. In $CO(NH_2)_2$ + NBPT and $CO(NH_2)_2$ + DMPP treatments, the cumulative loss of ammonia volatilization showed an extremely fast loss rate in the initial few days. However, under $CO(NH_2)_2$ + DMPP + NBPT treatment, the cumulative loss growth rate of soil ammonia volatilization was relatively slow. Overall, the cumulative volatilization loss order of ammonia throughout all the treatments was $CO(NH_2)_2$ > $CO(NH_2)_2$ + DMPP > $CO(NH_2)_2$ + NBPT > $CO(NH_2)_2$ + DMPP + NBPT, which indicated that the $CO(NH_2)_2$ + DMPP + NBPT treatment method could effectively inhibit the loss of nitrogen fertilizer in the soil.

Soil nitrogen runoff rate under different fertilization schemes

The nitrogen runoff loss rate demonstrated that the order of runoff loss rates of total nitrogen under the four fertilization ratios in sandy soil were $CO(NH_2)_2$ > $CO(NH_2)_2$ + DMPP > $CO(NH_2)_2$ + NBPT > $CO(NH_2)_2$ + DMPP + NBPT (Figure 3a). Under these four modes of treatment, the relative loss rates of total nitrogen runoff were approximately 126 - 185%, 109 - 162%, 68 - 102%, and 36 - 60%, respectively. In cohesive soil, the



(a)Sandy soil

(b)Clay soil

Figure 4. Nitrogen leaching loss rate under different fertilization ratios in two types of soil.

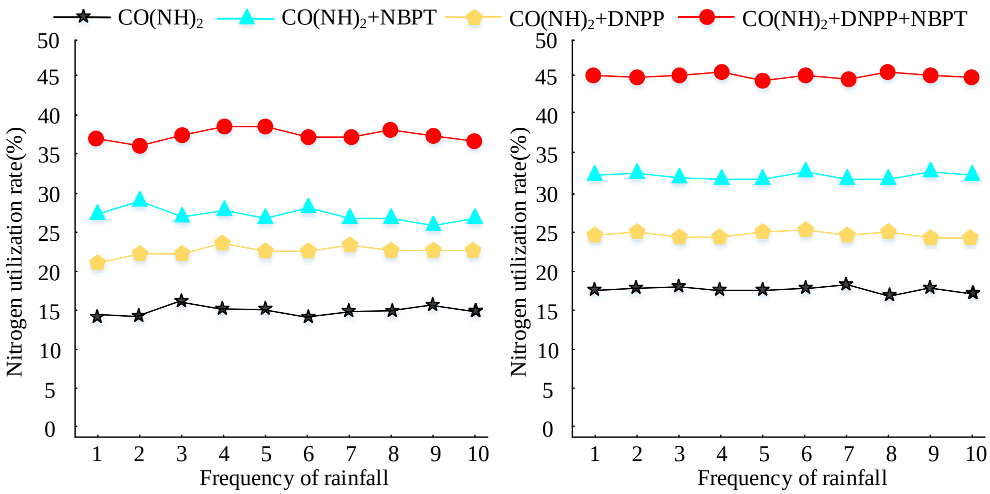
total nitrogen runoff loss rate was lower than that in sandy soil (Figure 3b). The total nitrogen runoff loss rates of $CO(NH_2)_2$, $CO(NH_2)_2$ + DMPP, $CO(NH_2)_2$ + NBPT, and $CO(NH_2)_2$ + DMPP + NBPT treatment modes were approximately 128 - 151%, 103 - 136%, 30 - 80%, and 34 - 45%, respectively.

Soil nitrogen leaching loss rate under different fertilization schemes

Compared to the runoff loss rate of soil nitrogen, the nitrogen leaching loss rate had increased significantly, but it was still the smallest under $CO(NH_2)_2$ + DMPP + NBPT treatment (Figure 4). In sandy soil, the total nitrogen leaching loss rates of $CO(NH_2)_2$, $CO(NH_2)_2$ + DMPP, $CO(NH_2)_2$ + NBPT, $CO(NH_2)_2$ + DMPP + NBPT treatment modes were approximately 289 - 341%, 202 - 253%, 106 - 154%, and 20 - 74%, respectively (Figure 4a). The leaching loss of nitrogen in clay soil was less than that in sandy soil. Under the treatment of $CO(NH_2)_2$ + DMPP + NBPT, the leaching loss rate of nitrogen was about 15 - 50% (Figure 4b). The results indicated that, when $CO(NH_2)_2$ was used alone as a nitrogen losses treatment method, the relative runoff loss rate of total nitrogen might be higher. In the $CO(NH_2)_2$ + DMPP treatment mode, DMPP inhibited the nitrification of nitrogen and slowed down the conversion of ammonia nitrogen to nitrate, which could delay the conversion rate of nitrogen in the soil and reduce the rate of nitrogen losses. In the $CO(NH_2)_2$ + NBPT treatment mode, NBPT could inhibit the activity of urease, delay the decomposition rate of urea, and reduce the loss of ammonia nitrogen. The combined utilization of nitrification inhibitors and urease inhibitors could further minimize total nitrogen loss. Nitrification inhibitors delayed the formation of nitrate, while urease inhibitors delayed the decomposition of ammonia nitrogen, resulting in longer retention time of nitrogen in the soil and reduced opportunities for loss.

Nitrogen fertilizer utilization efficiency in wheat under different fertilization schemes

The nitrogen fertilizer utilization efficiency analysis was conducted on 10 wheat samples collected from each treatment area. When $CO(NH_2)_2$ + DMPP + NBPT treatment was used in sandy soil, the nitrogen fertilizer utilization efficiency reached the highest level, approximately 36.1 to 37.4%. In contrast, the nitrogen fertilizer utilization efficiencies under the other three treatment modes were relatively low, ranging from 26.3 to 29.6% for $CO(NH_2)_2$ + NBPT, 21.3 to 23.7% for $CO(NH_2)_2$ + DMPP, and 14.6 to 16.2% for $CO(NH_2)_2$, respectively (Figure 5a). The nitrogen fertilizer utilization efficiency in clay soil was slightly higher than that in sandy soil.



(a)Sandy soil (b)Clay soil

Figure 5. Nitrogen utilization efficiency of wheat under different fertilization ratios in two types of soil.

In sticky soil, under the four treatment modes of $CO(NH_2)_2$ + DMPP + NBPT, $CO(NH_2)_2$ + NBPT, $CO(NH_2)_2$ + DMPP, and $CO(NH_2)_2$, the nitrogen fertilizer utilization efficiencies were about 44.3 - 45.6%, 32.6 - 33.7%, 24.1 - 25.3%, and 17.1 - 18.4%, respectively (Figure 5b). The efficiency of utilizing nitrogen fertilizer on wheat was significantly influenced by different treatment methods and soil types. In clay, the nitrogen loss and utilization efficiency was slightly higher than that in sandy soil. In sandy soil, the $CO(NH_2)_2$ + DMPP + NBPT treatment mode had the best effect, while in clay soil, the $CO(NH_2)_2$ + DMPP + NBPT treatment mode could also achieve higher nitrogen fertilizer utilization efficiency. $CO(NH_2)_2$ + DMPP + NBPT treatment could effectively improve the utilization efficiency of nitrogen fertilizer in wheat. The results indicated that this treatment mode could effectively reduce nitrogen losses and improve overall nitrogen utilization efficiency.

Conclusion

The results of this study suggested that (1) in different soil types, $CO(NH_2)_2$ + DMPP + NBPT could delay the rate of ammonia volatilization and reduce the peak value, thereby effectively reducing the loss of nitrogen fertilizer; (2) in different soil types, $CO(NH_2)_2$ + DMPP + NBPT could effectively inhibit the cumulative loss of soil ammonia volatilization; (3) clay soil exhibited lower rates of both runoff loss and nitrogen leaching loss compared to sandy soil. The application of $CO(NH_2)_2$ + DMPP + NBPT to soil led to a reduction in both the rates of runoff loss and nitrogen leaching loss; (4) the $CO(NH_2)_2$ + DMPP + NBPT model could effectively promote the nitrogen fertilizer utilization efficiency of wheat.

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