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Alteration of Nitrogen Fertilizer Forms Optimizes Nitrogen Balance in Drip-Irrigated Winter Wheat Systems of Northern China by Reducing Gaseous Nitrogen Losses

Ruixuan Hao, Junyi Mu, Xiaoting Xie, Qiqi Ha, Yuanyuan Wang, Wenbo Zhai, Peng Wu, Aixia Ren, Zhiqiang Gao, Ru Guo and Min Sun *

College of Agriculture, Shanxi Agricultural University/Key Laboratory of Sustainable Dryland Agriculture of Shanxi Province, Taiyuan 030031, China; haoruixuan123456@163.com (R.H.); mujunyi1997@163.com (J.M.); m13643577147@163.com (X.X.); 17795149954@163.com (Q.H.); 18303500427@163.com (Y.W.); b1679812126@163.com (W.Z.); agricultural_wp93@163.com (P.W.); rax_renaixia@163.com (A.R.); gaozhiqiang1964@126.com (Z.G.); guorurr@126.com (R.G.)
* Correspondence: sm_sunmin@126.com

Abstract

Winter wheat covers approximately 2.21 × 10^8 ha globally, making it the most widely cultivated cereal crop in the world. In recent years, integrated water and fertilizer management has significantly improved winter wheat yield and nitrogen use efficiency; however, quantitative assessments of nitrogen cycling under different fertilizer forms in such high-yield systems remain limited. From 2022 to 2024, a two-year field experiment was conducted in drip-irrigated winter wheat fields in northern China. Four nitrogen fertilizer forms were applied: nitrate nitrogen fertilizer (NON), ammonium nitrogen fertilizer (NHN), amide nitrogen fertilizer (CON), and urea ammonium nitrate fertilizer (UAN), along with an unfertilized control (CK). Compared with NON, NHN, and CON, UAN reduced cumulative N_2O emissions by 10.40–15.64% and NH_3 volatilization by 2.04–9.33% ($p < 0.05$). It also increased the leaf area index and biomass accumulation at maturity, as well as grain yield (3.70–10.28%), nitrogen harvest index (4.58–12.88%), and nitrogen use efficiency (12.14–39.25%) ($p < 0.05$). Furthermore, UAN significantly decreased the net nitrogen surplus (24.18–45.70%) and nitrogen balance values (25.64–55.82%) ($p < 0.05$). Correlation analysis indicated that the reduction in nitrogen balance was primarily attributed to lower N_2O emissions and improved nitrogen use efficiency ($p < 0.05$). In conclusion, the application of urea ammonium nitrate under integrated water–fertilizer management achieved higher yield, greater efficiency, and environmentally sustainable production in drip-irrigated winter wheat systems in northern China.

Keywords: winter wheat; drip irrigation; high yield; N_2O; NH_3; nitrogen balance

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Academic Editor: José Manuel Rato-Nunes

Received: 28 September 2025
Revised: 15 October 2025
Accepted: 16 October 2025
Published: 18 October 2025

Citation: Hao, R.; Mu, J.; Xie, X.; Ha, Q.; Wang, Y.; Zhai, W.; Wu, P.; Ren, A.; Gao, Z.; Guo, R.; et al. Alteration of Nitrogen Fertilizer Forms Optimizes Nitrogen Balance in Drip-Irrigated Winter Wheat Systems of Northern China by Reducing Gaseous Nitrogen Losses. *Agriculture* **2025**, *15*, 2164. https://doi.org/10.3390/agriculture15202164

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1. Introduction

Northern China is the major winter wheat production region and plays a vital role in ensuring national food security. However, water scarcity and low nitrogen (N) use efficiency have long constrained high yields and sustainable development in this area. In recent years, water–fertilizer integration technology has been increasingly adopted in winter wheat production across northern China [1]. By enabling precise irrigation and fertilization, this approach synchronizes water and nitrogen supply, thereby improving water use efficiency (WUE) and nitrogen use efficiency (NUE). Studies have shown that, compared

with traditional flood irrigation and broadcast fertilization, water–fertilizer integration with proper N management can increase winter wheat yield by 10.4–12.6%, with maximum yields reaching 12,080 kg ha^{-1} [2]. Multi-site trials across northern China have consistently reported yields exceeding 10,500 kg ha^{-1}, representing a super-high-yield level [2–4]. Yield improvements under this system are mainly attributed to increases in spike number and thousand-grain weight at maturity, enhanced post-anthesis biomass accumulation, and greater flag leaf photosynthetic activity [4]. Moreover, water–fertilizer integration improves the spatial and temporal coordination of roots, nutrients, and water, significantly enhancing WUE and NUE while reducing deep-soil nitrate (NO_3^--N) accumulation [5]. Under such systems, different nitrogen fertilizer forms (urea, ammonium nitrate, and ammonium sulfate) show distinct effects on crop yield, WUE, NUE, and nitrogen losses [6]. Using the ^{15}N labeling technique, studies on drip-fertigated winter wheat revealed that nitrate-N exhibited significantly higher NUE than ammonium-N and urea [7]. Modeling analyses further indicate that nationwide adoption of water–fertilizer integration in China could increase grain production by approximately 12% on average, raise WUE and NUE by 26.4% and 34.3%, respectively, and effectively mitigate N leaching [8]. Therefore, water–fertilizer integration provides a crucial technical foundation for overcoming water and nutrient constraints in the arid and semi-arid regions of northern China, enabling high-yield, efficient, and environmentally sustainable winter wheat production.

N is a key element for plant growth, and the availability of soil N exerts a significant influence on crop development [9]. Fertilizer application can improve crop growth and ultimately increase yield. Since the Green Revolution, synthetic fertilizers have been widely used to meet crop N demands. At present, China applies approximately 3×10^{11} kg of N fertilizer (pure N) annually, accounting for one-third of global consumption [10]. Although further increases in N input may help to meet future food demand, the resource-intensive production pattern in agriculture has led to low NUE and considerable N losses (40–50%), particularly in the arid and semi-arid regions of northern China [11]. Studies have shown that applying all N fertilizer as a basal dose results in up to 80% of N remaining in the soil as inorganic forms that cannot be taken up by winter wheat, thereby exacerbating environmental risks [12]. Under water–fertilizer integration, inappropriate irrigation and fertilization practices can aggravate N losses from farmland, with NO_3^--N leaching polluting aquatic systems and gaseous losses of nitrous oxide (N_2O) and ammonia (NH_3) increasing environmental burdens [13]. Moreover, when applied as single N forms, fertilizers often exhibit spatial and temporal mismatches between soil N availability and crop root uptake dynamics, leading to inefficiencies where part of the N is either lost as gaseous emissions or remains in the soil [14]. Therefore, within the framework of high-yield water–fertilizer integration systems for winter wheat, optimizing fertilizer forms may represent an effective strategy to further enhance yield and NUE while mitigating N losses.

To improve NUE in wheat, extensive studies have been conducted on N fertilizer types, application rates, and their combination with N inhibitors. It has been reported that ammonium-based N fertilizers promote chlorophyll formation during the seedling stage, thereby enhancing wheat growth [15]. However, some studies suggest that N fertilizer forms have no significant effect on wheat yield [16]. This inconsistency may be attributed to differences in soil type and inherent fertility, as well as the distinct transformation processes of different N fertilizers in soil, which ultimately affect N uptake by wheat [14]. Regardless of whether crops prefer ammonium or nitrate, mixed ammonium–nitrate fertilizers generally lead to higher yields compared with sole ammonium- or nitrate-based fertilizers, while leaving less residual N in the soil. This may be because crops exhibit different N preferences across growth stages, thereby making better use of soil-available N [17]. Research on N application rates has demonstrated that appropriate planting density and optimal N input

are beneficial for maintaining high yield and improving NUE [18], with modeling studies further supporting these findings [19]. In addition, previous studies have investigated the effects of N management strategies on wheat yield, NUE, and soil N accumulation. Rational N management can supply sufficient N during key growth stages, thereby improving wheat N uptake and NUE while reducing residual soil N accumulation [20]. Moreover, nitrification inhibitors have been shown to improve wheat yield and NUE by maintaining higher ammonium (NH_4^+-N) concentrations and NO_3^--N concentrations in soil, thus enhancing NUE [21]. Despite these advances, most studies have been based on conventional urea or other solid N fertilizers. With the continuous advancement of fertilizer reduction and efficiency enhancement technologies in northern China, and given the pronounced advantages of water-soluble and liquid nitrogen fertilizers in water–fertilizer integration systems, liquid urea ammonium nitrate (UAN) fertilizer demonstrates great potential for widespread application.

Northern China is the major production region of winter wheat and plays a crucial role in ensuring national food security. To overcome the constraints of limited water resources and low NUE on wheat yield, recent studies have mainly focused on the effects of water–fertilizer integration on yield improvement and efficiency enhancement. However, under high-yield cultivation systems, quantitative studies on the impacts of different N fertilizer forms on soil mineral N residuals and gaseous N emissions in winter wheat fields remain limited. Therefore, a two-year field experiment was conducted in high-yield demonstration fields of the Loess Plateau with the objectives of: (1) quantifying the effects of different N fertilizer forms on soil mineral N residuals and gaseous N emissions during the winter wheat growing season; (2) determining their impacts on crop growth, yield, and nitrogen use efficiency; and (3) establishing a suitable fertilization strategy for high-yield drip-irrigated winter wheat systems in northern China to achieve high yield, high efficiency, and sustainable production. This study hypothesizes that, compared with single-form N fertilizers, compound N fertilizers could increase winter wheat yield while optimizing nitrogen balance in agroecosystems.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted over two consecutive years (2022–2024) at the Shenfeng Village experimental station of Shanxi Agricultural University (37°42′ N, 112°53′ E). The site is located in the northeastern part of the Jinzhong Basin on the Loess Plateau, China, at an altitude of 791 m. The region is characterized by a warm temperate continental climate typical of arid and semi-arid zones, with a frost-free period of 159–167 days, an annual mean temperature of 11 °C, annual sunshine duration of 2500–2600 h, and an average annual precipitation of approximately 458 mm. Before the experiment, the soil had the following properties: soil organic matter 12.57 g kg^{-1}, alkali-hydrolysable N 1.01 g kg^{-1}, available P 33.73 mg kg^{-1}, and available K 126.33 mg kg^{-1}. Precipitation and mean daily temperature during the experimental period (2022–2024) are presented in Figure 1 (data collected from an on-site meteorological station). The region follows a single-cropping system with winter wheat grown annually, and the experimental field had been continuously cultivated with winter wheat prior to the initiation of this study.

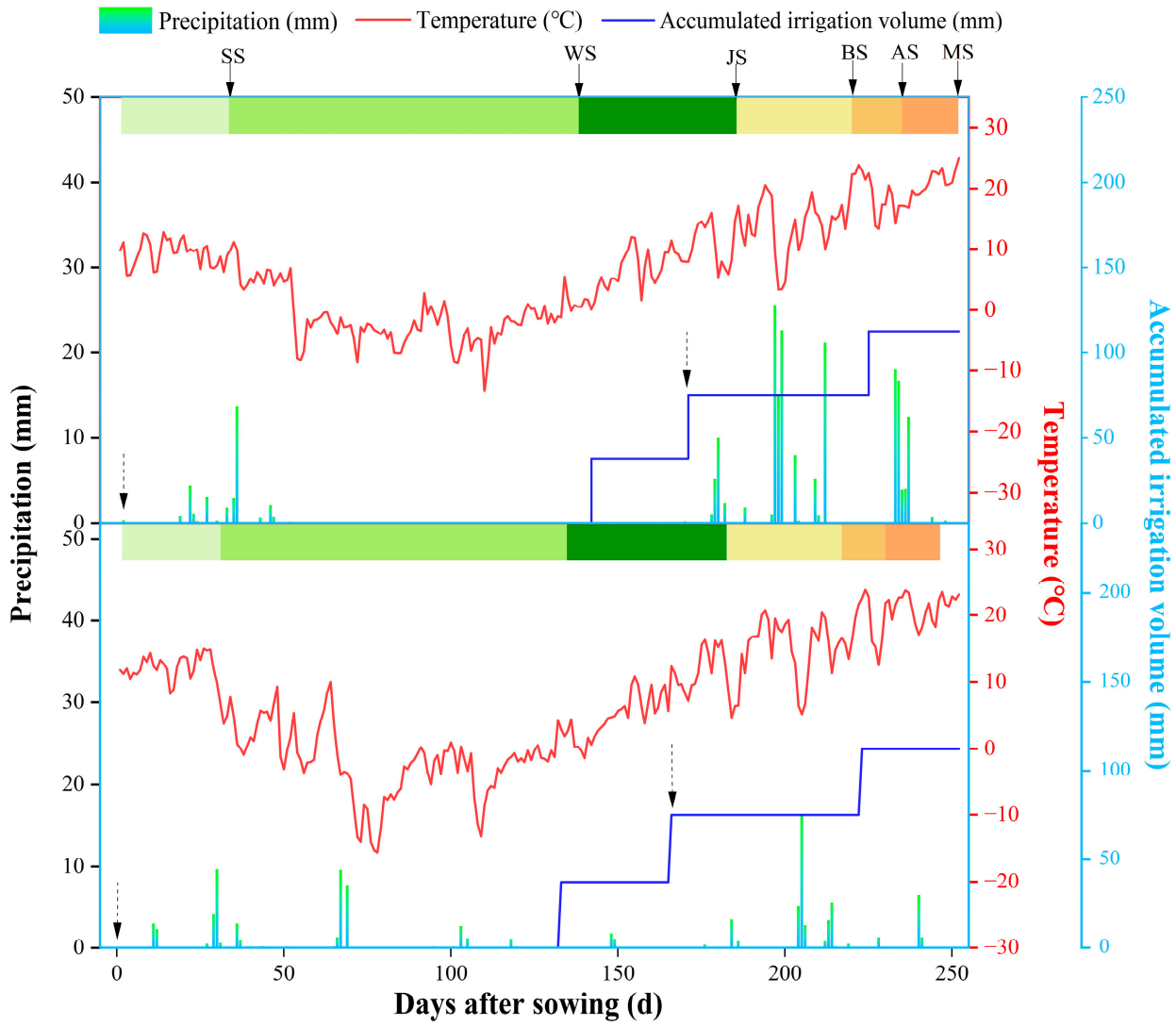


Figure 1. Daily precipitation, mean daily temperature, and accumulated irrigation volume during the wheat growing seasons from 2022 to 2024 at the experimental site. The dashed arrows indicate the timing of fertilization. The different colored blocks represent the growth stages of winter wheat: SS, seedling stage; WS, wintering stage; JS, jointing stage; BS, booting stage; AS, anthesis stage; and MS, maturity stage.

2.2. Field Management and Experimental Design

The experiment followed a single-factor randomized block design with five treatments: nitrate N fertilizer (NON, $NaNO_3$, total N 16%), ammonium N fertilizer (NHN, $(NH_4)_2SO_4$, total N 21%), amide N fertilizer (CON, urea, $CO(NH_2)_2$, total N 46%), urea ammonium nitrate fertilizer (UAN, liquid, total N 32%, including nitrate N 8%, ammonium N 8%, and amide N 16%), and a control without fertilizer (CK). Each treatment had three replicates, giving 15 plots of 50 m^2 each (5 m × 10 m). The winter wheat cultivar (*Triticum aestivum* L.) 'Jintai 182' was sown on 5 October 2022 and 25 September 2023 and harvested on 28 June 2023 and 22 June 2024. The sowing density was 1.8×10^6 plants ha^{-1} with wide-drill broadcasting. Straw residues were incorporated into the 10–15 cm soil layer, seeding depth was 3–5 cm, row spacing was 22–25 cm, and band width was 10–12 cm (Figure 2). Before sowing, 90 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1} were applied as basal fertilizers. Liquid N fertilizers were diluted and sprayed evenly on the plots. An additional 90 kg N ha^{-1} was applied at the jointing stage through fertigation, resulting in a total N input of 180 kg ha^{-1}. During the winter wheat growing season, soil moisture-based

supplemental irrigation was applied using drip tapes (Figure 1), and the irrigation volume was calculated according to the following formula [22]:

$$M = 10 \times \gamma \times H \times (\beta_i - \beta_j) \quad (1)$$

where M (mm) is the irrigation amount, γ (g cm^{-3}) is the soil bulk density at 0–40 cm depth, H (cm) is the soil layer depth, β_i (%) is the target soil moisture content, and β_j (%) is the soil moisture content before irrigation.

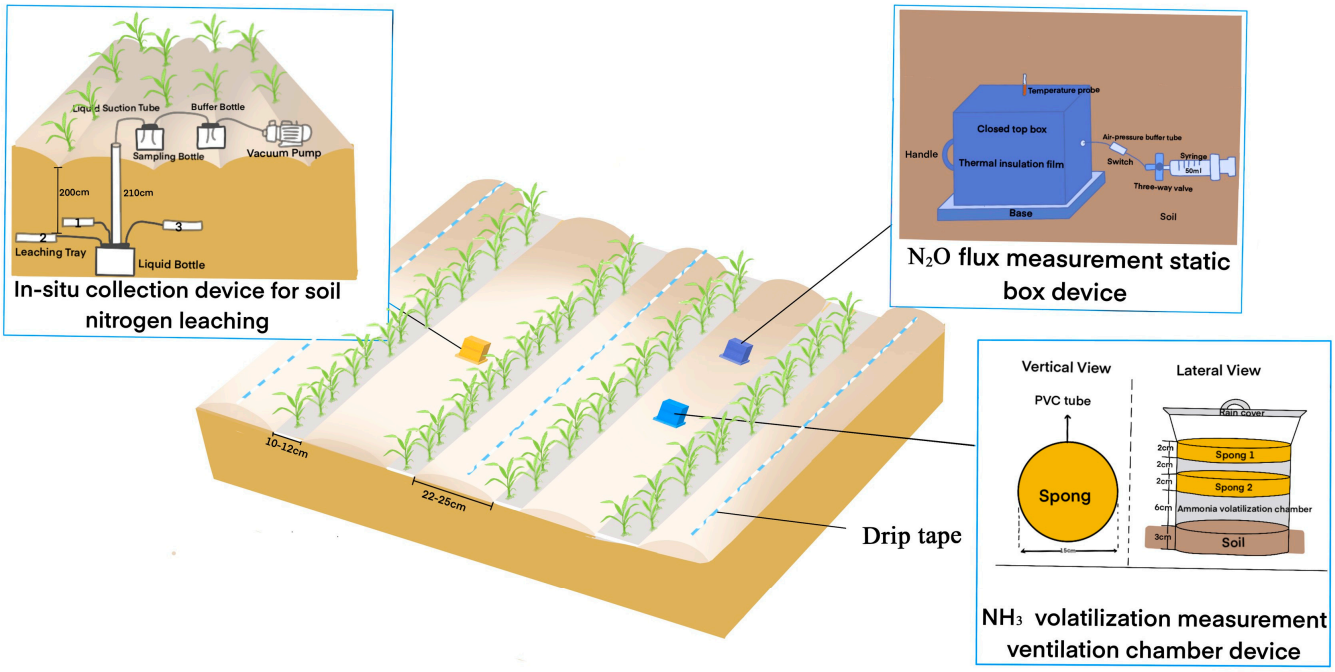


Figure 2. Schematic diagram of the drip tape, ventilation chamber, static chamber, and N leaching collection device in the experimental plots.

Field capacity was measured using a handheld soil moisture meter (HS2 Hydro Sense II, Campbell, CA, USA). Irrigation was applied at the jointing and anthesis stages when field capacity dropped below 65%, and water was replenished to 80% of field capacity [23]. During the 2022–2024 winter wheat growing seasons, irrigation was applied twice at the jointing stage and once at the anthesis stage, with 37.5 mm of water each time (Figure 1). All other field management practices followed conventional high-yield cultivation practices for winter wheat.

2.3. Measurements and Calculation Methods

2.3.1. Soil NO_3^--N and NH_4^+-N Measurement

Sampling at key growth stages of winter wheat, including the jointing, booting, flowering, and maturity stages, can accurately capture the physiological and biochemical dynamics during these critical periods while establishing the temporal foundation for modeling nitrogen cycling in winter wheat. Therefore, during the winter wheat growing seasons from 2022 to 2024, soil samples were collected at the jointing, booting, anthesis, and maturity stages. In each plot, five sampling points were randomly selected using a 5-cm diameter soil auger, and soil cores were taken at 20-cm intervals from 0 to 100 cm depth. The concentrations of NO_3^--N and NH_4^+-N in the soil were determined using a continuous flow analyzer (Autoanalyzer 3, SEAL, Norderstedt, Germany).

2.3.2. Measurement of N_2O Flux

The N_2O fluxes at the experimental site were measured using the static chamber–gas chromatography method. The static chamber consisted of a sampling box and a base. The sampling box was a polyethylene cube (0.6 m × 0.6 m × 0.6 m) with a layer of thermal insulation material on the surface to minimize temperature fluctuations inside the chamber during sampling. A battery-powered miniature fan was installed in a groove at the top to ensure continuous air circulation. The base was a quadrangular structure (0.6 m × 0.6 m × 0.2 m; Figure 2). After wheat sowing, the base was inserted into the soil at the center of each plot to a depth of approximately 10 cm. The static chamber was sealed by filling the groove with water, and gas samples were collected at 0, 10, 20, and 30 min after chamber closure using 50 mL syringes. Gas sampling was conducted every five days during the experiment, daily in the first week after rainfall and fertilization, every two days in the second week, and every three days in the third week. N_2O concentrations were analyzed using a gas chromatograph (GC-2010 Pro, Shimadzu, Kyoto, Japan), and the N_2O flux was calculated according to the following equation [24]:

$$f = \rho \times h \times dc/dt \times 273/(273 + T) \quad (2)$$

where f (mg m^{-2} h^{-1}) is the N_2O flux, ρ (kg m^{-3}) is the density of N_2O under standard conditions, h (m) is the height of the static chamber, dc/dt (mg kg^{-1} h^{-1}) is the rate of change in N_2O concentration within the chamber per unit time, 273 is the absolute temperature correction factor, and T (°C) is the mean air temperature inside the chamber at the time of sampling.

The cumulative N_2O fluxes during the winter wheat growing season were estimated using the following equation [25]:

$$F = \sum_{i=1}^{n} \left(\frac{f_i + f_{i+1}}{2} \right) \times (t_{i+1} - t_i) \times 24 \quad (3)$$

where F (kg ha^{-1}) is the cumulative N_2O flux, i is the i-th sampling time, and $(t_{i+1} - t_i)$ (d) is the number of days between two consecutive sampling events.

2.3.3. Measurement of NH_3 Volatilization

NH_3 volatilization in the experimental field was measured using the continuous airflow chamber method. The chamber consisted of a bottomless polyvinyl chloride (PVC) cylinder with an outer diameter of 16 cm, an inner diameter of 15 cm, and a height of 10 cm. Two sponges (16 cm in diameter, 2 cm in thickness) soaked with 15 mL of glycerol phosphate solution were placed inside the chamber to capture NH_3 gas (Figure 2). After wheat sowing, the chambers were placed at the center of each plot. Gas sampling was performed once daily during the first week after fertilization, every two days in the second week, every three days in the third week, and approximately every five days thereafter until NH_3 volatilization was no longer detectable. For each sampling, the chamber was inserted 3 cm into the soil. After sampling, the sponge at the bottom of the chamber was removed and immediately sealed in a plastic bag, and a new sponge was placed in the chamber. The collected sponges were promptly returned to the laboratory for extraction, and the NH_4^+-N concentration in the extracts was determined using a continuous flow analyzer (Autoanalyzer 3, SEAL, Germany). The NH_3 volatilization flux was calculated according to the following equation [26]:

$$N_v = \frac{M}{S \times D \times 100} \quad (4)$$

where N_v (kg N ha^{-1} d^{-1}) is the soil NH_3 volatilization rate, M (mg) is the amount of NH_4^+-N absorbed in the sponge, S (m^2) is the cross-sectional area of the chamber, and D (d) is the number of days the sponge was exposed in the chamber. The cumulative NH_3 volatilization was calculated as the sum of the product of NH_3 volatilization rate and collection days for each sample.

2.3.4. Leaf Area Index, Dry Matter Accumulation, and Plant N Measurements

Leaf area index (LAI) was measured using a canopy analyzer (SunScan, Delta-T, Burwell, UK) at the jointing, booting, anthesis, 15 days after anthesis, and maturity stages of winter wheat. On clear and cloudless days, the probe of the instrument was placed at the bottom of the wheat canopy to record LAI values.

At the wintering, jointing, booting, anthesis, and maturity stages of winter wheat, 20 representative plants were collected from each plot. At the wintering and jointing stages, whole plants were sampled; at anthesis, plants were separated into leaves, stems + sheaths, and spikes; and at maturity, plants were separated into grains, leaves, stems + sheaths, and glumes + rachis. Samples were first oven-dried at 105 °C for 30 min to inactivate enzymes, then dried at 75 °C to a constant weight, while grains were dried separately at 65 °C. The dry matter was then determined.

After drying, plant organs were ground using a plant mill, and their N concentrations were determined by the H_2SO_4–H_2O_2 digestion method followed by an automatic Kjeldahl analyzer (VAPODEST 200, Gerhardt, Königswinter, Germany). The N accumulation of each organ was calculated as the product of its N concentration and dry matter weight.

2.3.5. Grain Yield and Yield Component Measurement

At maturity, five uniform 0.667 m^2 quadrats were selected from each plot to measure grain yield. In addition, a 20 m^2 area was harvested in each plot to determine yield components, including spike number per unit area, grains per spike, and thousand-grain weight. Grain yield was adjusted to a standard moisture content of 12.5% according to the national standard of China (GB 1351-2023) [27].

2.3.6. Calculation of Harvest Index, N Harvest Index, and NUE

Harvest index and N harvest index were calculated using the following equations [28]:

$$HI = \frac{Yield}{Biomass} \times 100\% \quad (5)$$

$$NHI = \frac{GrainN}{BiomassN} \times 100\% \quad (6)$$

where HI is the harvest index (HI), $Yield$ (kg ha^{-1}) is the grain yield of winter wheat, $Biomass$ (kg ha^{-1}) is the dry matter of winter wheat, NNI is the N harvest index (NHI), $GrainN$ (kg ha^{-1}) is the N accumulation in wheat grain, and $BiomassN$ (kg ha^{-1}) is the total N accumulation in wheat plants.

NUE was calculated using the following equation [29]:

$$NUE = \frac{Y_1 - Y_2}{N_{applied}} \quad (7)$$

where NUE is the nitrogen use efficiency (NUE), Y_1 (kg ha^{-1}) is the total dry matter of winter wheat under N fertilization, Y_2 (kg ha^{-1}) is the total dry matter of winter wheat without N fertilization, and $N_{applied}$ (kg N ha^{-1}) is the amount of N fertilizer applied.

2.3.7. N Balance Calculation

N inputs consisted of four components: atmospheric N deposition (wet and dry), non-symbiotic N fixation, fertilizer N, and seed N content. The calculation formula was as follows [30]:

$$N_{input} = N_f + N_a + N_{n-s} + N_s \quad (8)$$

where N_{input} (kg N ha^{-1}) is the total N input in winter wheat fields, N_f (kg N ha^{-1}) is fertilizer N, N_a (kg N ha^{-1}) is atmospheric N deposition, N_{n-s} (kg N ha^{-1}) is non-symbiotic N fixation, and N_s (kg N ha^{-1}) is seed N content.

Atmospheric N deposition: During the winter wheat growing season, precipitation samples were collected after each rainfall event from the on-site meteorological station, and inorganic N concentrations were determined using a continuous flow analyzer (Autoanalyzer 3, SEAL, Germany). The N input from precipitation was calculated as the product of rainfall amount and inorganic N concentration, and the sum of N inputs over the growing season was defined as atmospheric wet N deposition. In eastern China (including Shanxi Province), the annual atmospheric dry N deposition ranged from 20 to 45 kg N ha^{-1} yr^{-1} during 2011–2020, with future levels estimated at approximately 35 kg N ha^{-1} yr^{-1} [31]. Therefore, in this study, the atmospheric dry N deposition was set to 35 kg N ha^{-1}.

Non-symbiotic N fixation: For non-leguminous crops, non-symbiotic N fixation generally ranges from 4.5 to 20 kg ha^{-1} yr^{-1}. Based on the latest findings of Guo et al. [32], the non-symbiotic N fixation of winter wheat in this study was set to 15 kg ha^{-1} yr^{-1}.

Seed N content: Before sowing each year, seed samples were collected, and seed N concentrations were determined using the H_2SO_4–H_2O_2 digestion method with an automatic Kjeldahl analyzer (VAPODEST 200, Gerhardt, Germany). Seed N content was calculated as the product of seed N concentration and seeding rate.

N outputs: N outputs included harvested N removal, ammonia volatilization N loss, nitrous oxide N loss, N gas emissions, surface runoff, soil erosion, and N leaching. Since the experimental site was flat and no surface runoff or soil erosion was observed during the winter wheat growing seasons, these two components were excluded. The N output was calculated according to the following equation [33]:

$$N_{output} = N_r + N_l + N_v + N_d + N_n \quad (9)$$

where N_{output} (kg N ha^{-1}) is the total N output from winter wheat fields, N_r (kg N ha^{-1}) is harvested N removal, N_l (kg N ha^{-1}) is N leaching, N_v (kg N ha^{-1}) is ammonia volatilization N loss, N_d (kg N ha^{-1}) is nitrous oxide N loss, and N_n (kg N ha^{-1}) is N gas emissions.

N leaching: At a depth of 200 cm in each plot, a drainage pan (19 cm in diameter, 5 cm in height) was installed to collect soil leachates (Figure 2). Soil leachates were collected on the 1st, 2nd, 3rd, and 5th days after each irrigation and rainfall event using a vacuum pump. The leachates were transported to the laboratory, where their N concentrations were determined using a continuous flow analyzer (Autoanalyzer 3, SEAL, Germany). N leaching was calculated using the following equation [34]:

$$N_l = \sum_{i=1}^{n} \frac{C_i \times V_i}{S} \times 0.01 \quad (10)$$

where N_l (kg N ha^{-1}) is the amount of N leaching, C_i (mg L^{-1}) is the nitrate concentration in the leachate, V_i (L) is the volume of leachate, n is the number of leachate samples, and S (m^2) is the cross-sectional area of the drainage pan.

N gas emissions: Globally, the N_2/N_2O ratio ranges from 2.2 to 4.6, and it is projected to be approximately 3.5 by 2050 [35]. Therefore, in this study, N_2 emissions were estimated as 3.5 times the N_2O emissions.

The calculation formulas for net N surplus and N balance were as follows [36]:

$$N_{NS} = N_{input} - N_r \quad (11)$$

$$N_B = N_{input} - N_{output} - \Delta TN \quad (12)$$

where N_{NS} (kg N ha^{-1}) is the net N surplus, N_r (kg N ha^{-1}) is harvested N removal, N_B (kg N ha^{-1}) is the N balance, and ΔTN (kg N ha^{-1}) is the change in total soil N storage between pre-sowing and post-harvest.

2.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed to determine the significant differences ($p < 0.05$) among treatments in cumulative N_2O emissions, cumulative NH_3 emissions, yield, and its components. Pearson correlation coefficients were calculated to analyze the relationships between soil NO_3^--N and NH_4^+-N concentrations, dry matter, LAI, NH_3, N_2O, NUE, and yield at different growth stages of winter wheat. Statistical analyses, including ANOVA and least significant difference (LSD) tests, were conducted using SPSS 27 (SPSS Inc., Chicago, IL, USA). Figures were generated using Origin 2025b (Origin Lab Inc., Northampton, MA, USA), and tables were prepared using Excel 2021 (Microsoft, Redmond, WA, USA).

3. Results

3.1. Soil NO_3^--N and NH_4^+-N

Compared with CK, all fertilization treatments significantly increased soil NO_3^--N (by 80.26–109.83%) and NH_4^+-N (by 156.80–240.80%) contents in the 0–100 cm soil profile during the winter wheat growing season (Figure 3; $p < 0.05$). At the jointing, booting, and anthesis stages, UAN significantly increased NO_3^--N content in the 80–100 cm soil layer by 9.45–39.19% compared with NHN and CON ($p < 0.05$). In contrast, NHN increased NH_4^+-N content in the 0–100 cm soil profile by 10.59–28.24% at the jointing stage compared with the other N forms, although the differences were not significant ($p > 0.05$).

Compared with NON, NHN, and CON, UAN significantly increased soil NO_3^--N residues in the 0–100 cm soil profile at maturity by 4.51–11.38% (Figure 4; $p < 0.05$). UAN also resulted in the highest soil NH_4^+-N residues at maturity among all N fertilizer forms, although the differences from NHN and CON were not significant ($p < 0.05$).

3.2. N_2O Flux and NH_3 Volatilization

For the NON and UAN treatments, N_2O fluxes peaked 2–3 days after fertilization, whereas the peak occurred 4–5 days after fertilization under the NHN treatment and 5–6 days under the CON treatment. During periods without fertilization events in the winter wheat growing season, N_2O fluxes in all fertilization treatments remained at relatively low levels (Figure 5). The peak N_2O fluxes followed the order NON > NHN > CON > UAN. Compared with other N fertilizer forms (NON, NHN, and CON), UAN reduced cumulative N_2O emissions by 10.40–15.64% ($p < 0.05$).

During the winter wheat growing season, the peak of soil NH_3 volatilization under different N fertilizer forms occurred 4–6 days after fertilization and declined to very low levels after 16 days (Figure 6). Compared with CON, NON, NHN, and UAN significantly reduced cumulative NH_3 volatilization by 4.50–10.49% ($p < 0.05$). Overall, UAN was

more effective than the other N forms in reducing gaseous N (N_2O and NH_3) losses (Figures 5 and 6).

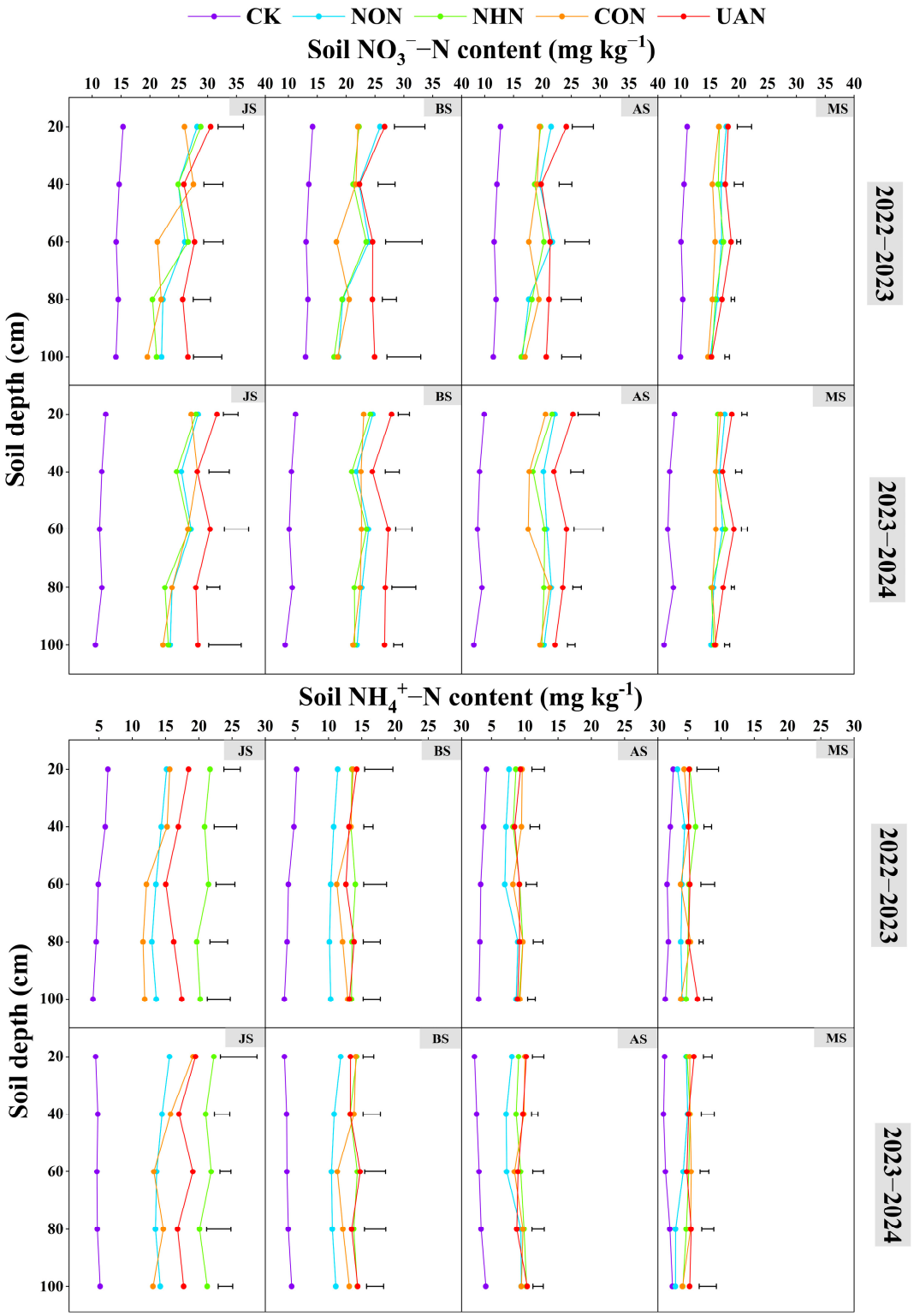


Figure 3. Soil NO_3^--N and NH_4^+-N contents in the 0–100 cm soil profile at different growth stages of winter wheat under different N fertilizer forms from 2022 to 2024. CK: no N application; NON: nitrate N fertilizer ($NaNO_3$); NHN: ammonium N fertilizer ($(NH_4)_2SO_4$); CON: amide N fertilizer ($CO(NH_2)_2$); UAN: urea ammonium nitrate fertilizer ($CO(NH_2)_2$ + NH_4NO_3). Horizontal error bars indicate LSD at $p = 0.05$ (n = 4).

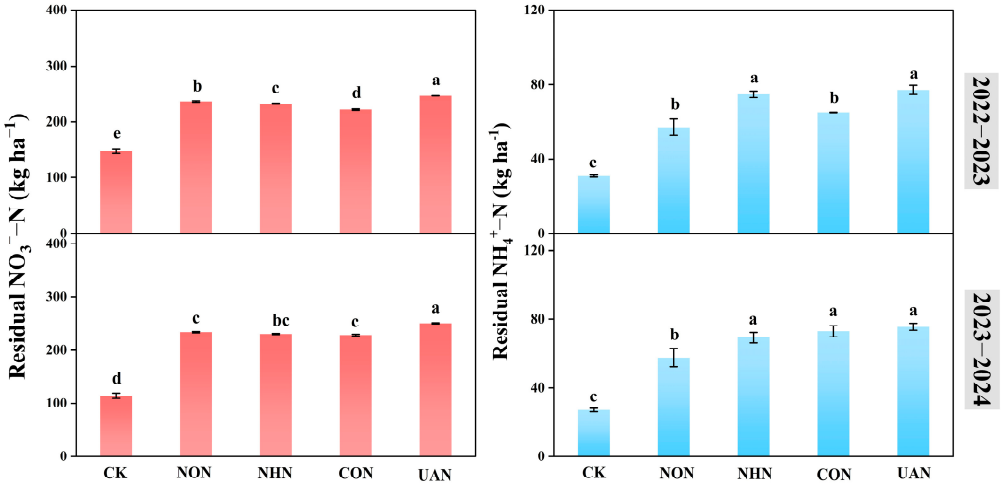


Figure 4. NO_3^--N and NH_4^+-N contents in the 0–100 cm soil profile at maturity under different N fertilizer forms from 2022 to 2024. Vertical error bars represent standard deviation, and different lowercase letters indicate significant differences among treatments at the p = 0.05 (n = 4) level.

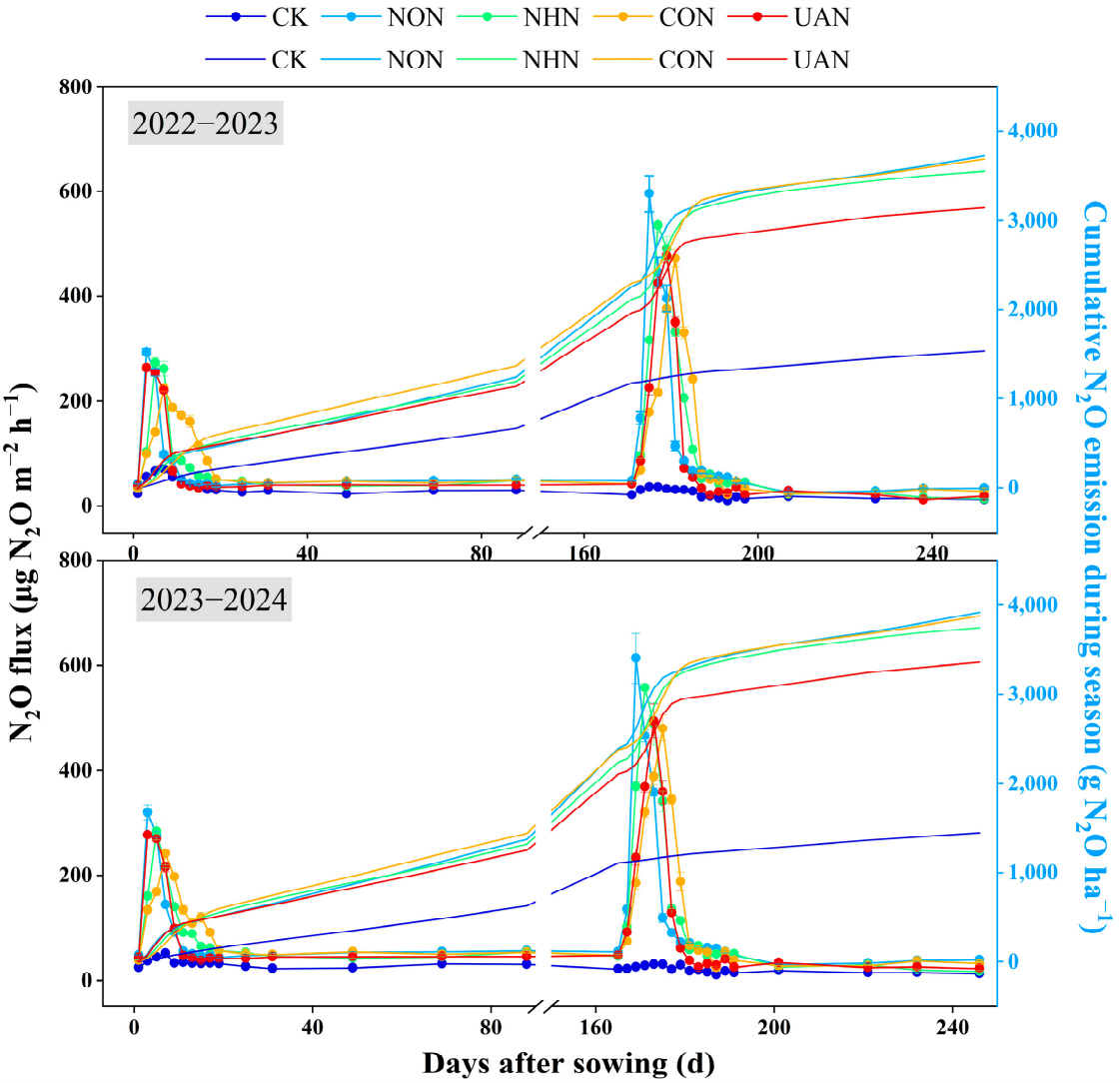


Figure 5. N_2O fluxes and cumulative N_2O emissions during the winter wheat growing seasons under different N fertilizer forms from 2022 to 2024. Vertical error bars represent standard deviation.

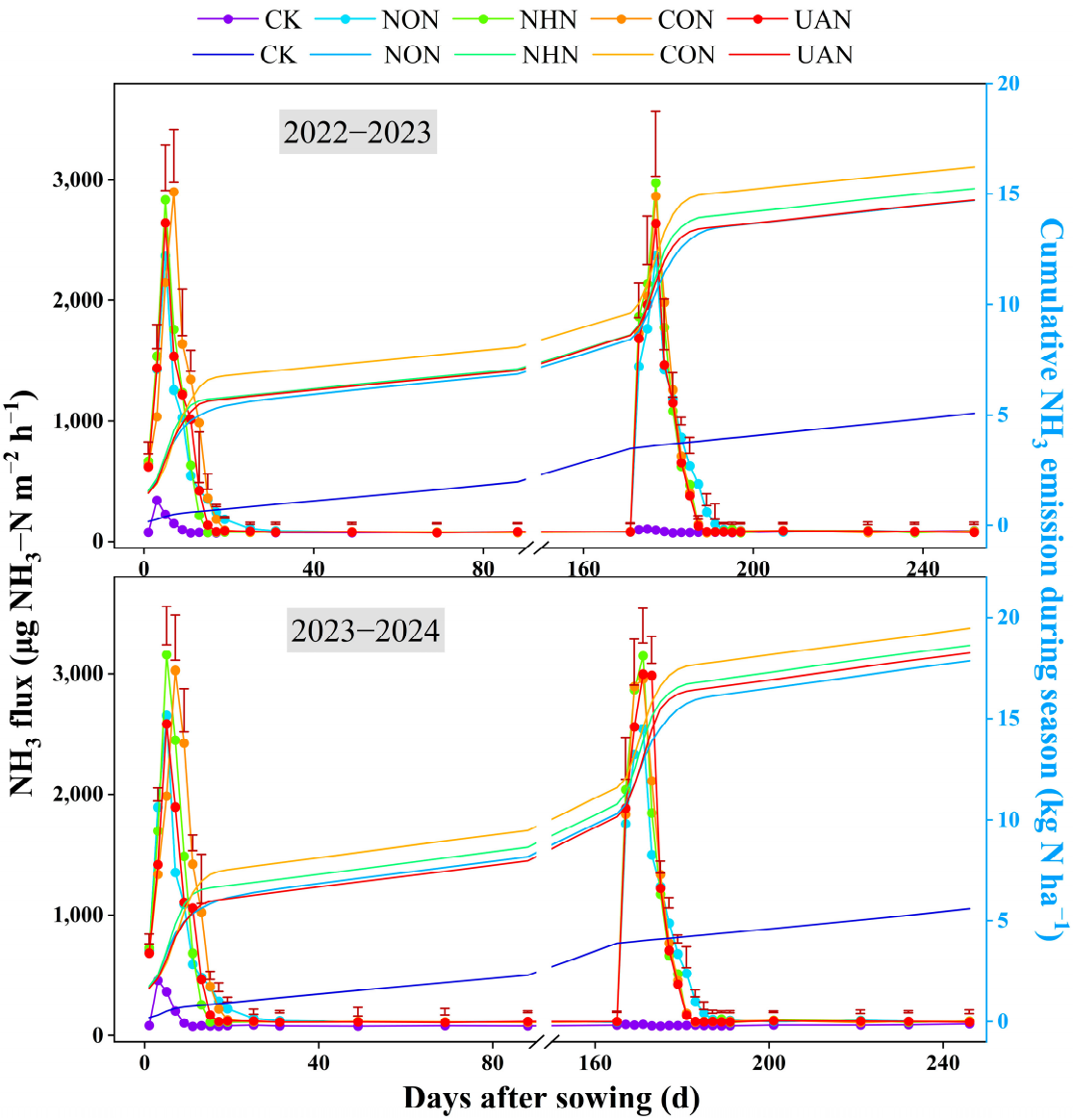


Figure 6. NH_3 volatilization fluxes and cumulative NH_3 emissions during the winter wheat growing seasons under different N fertilizer forms from 2022 to 2024. Vertical error bars indicate LSD at $p = 0.05$ (n = 4).

3.3. LAI and Dry Matter

As the winter wheat growth period progressed, the LAI first increased and then decreased, while the rate of change in dry matter increased after the jointing stage (Figure 7). Compared with the CK, fertilization significantly increased LAI and dry matter after the jointing stage ($p < 0.05$). Relative to other N fertilizer forms (NON, NHN, and CON), the application of UAN significantly increased LAI by 1.50–5.92% at the booting, 15 days after anthesis, and maturity stages, and significantly increased dry matter by 3.57–9.35% at maturity ($p < 0.05$).

3.4. Winter Wheat Yield and NUE

Fertilization significantly increased winter wheat yield by 36.95–59.54% compared with the CK (Table 1, $p < 0.05$). Application of UAN significantly increased spike number (by 1.69–26.34%) and kernels per spike (by 4.93–12.20%) compared with other N fertilizer forms (NON, NHN, and CON), thereby significantly increasing yield by 3.70–10.28%

($p < 0.05$). In addition, UAN application significantly increased the NHI and NUE by 4.58–12.88% and 12.14–39.25%, respectively, compared with the other N fertilizer forms (NON, NHN, and CON) ($p < 0.05$; Table 1; Figure 7).

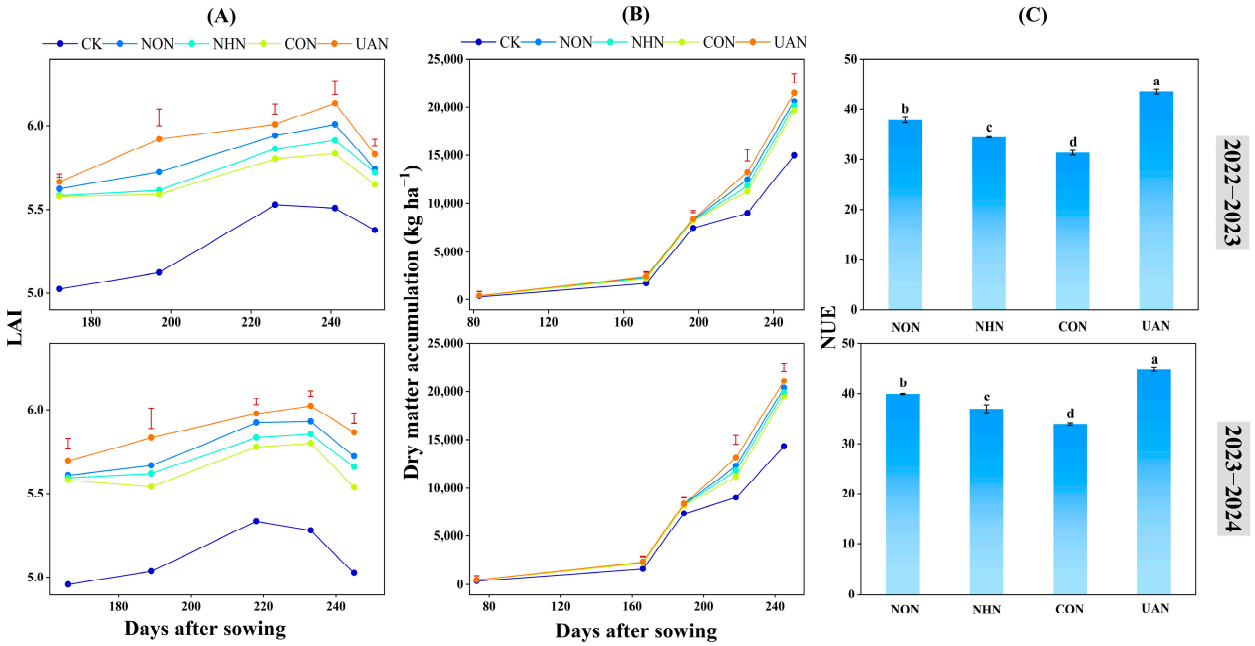


Figure 7. Effects of different N fertilizer forms on LAI (**A**), dry matter accumulation (**B**), and NUE (**C**) of winter wheat from 2022 to 2024. In (**A**,**B**), vertical error bars indicate LSD values at $p = 0.05$ (n = 4), while in (**C**), vertical error bars represent standard deviation; different lowercase letters indicate significant differences among treatments at the $p = 0.05$ (n = 3) level.

Table 1. Effects of different N fertilizer forms on winter wheat yield and its components, HI, and NHI from 2022 to 2024.

Year	N Fertilizer Forms	Ear Number (10^4 ha^{-1})	Grain Number per Ear	1000-Grain Weight (g)	Yield (kg ha^{-1})	HI (%)	NHI (%)
2022–2023	CK	408.29 e	34.23 c	38.77 b	7624.28 d	51.38 d	49.5 d
	NON	643.77 b	47.24 ab	47.86 a	10,846.34 b	53.94 ab	62.37 b
	NHN	578.31 c	45.98 b	48.34 a	10,459.32 c	52.22 bc	61.58 b
	CON	541.72 d	44.36 b	47.25 a	10,441.34 c	54.76 cd	58.39 c
	UAN	684.37 a	49.57 a	49.69 a	11,247.65 a	53.07 a	65.91 a
2023–2024	CK	384.21 c	33.91 c	37.26 b	7013.54 d	50.51 c	48.77 d
	NON	663.13a	46.28 b	46.53 a	10,475.36 b	52.66 ab	61.29 b
	NHN	561.32 b	46.27 b	46.73 a	10,157.32 c	52.03 ab	60.13 b
	CON	533.73 b	44.51 b	46.33 a	10,146.39 c	53.42 bc	56.87 c
	UAN	674.32 a	49.94 a	47.71 a	11,189.31 a	53.67 a	64.1 a

Lowercase letters within the same column indicate significant differences among different N fertilizer treatments in the same winter wheat growing season at the $p = 0.05$ (n = 4) level.

3.5. N Balance

Application of different N fertilizer forms had a significant effect on the N balance of winter wheat fields ($p < 0.05$), showing a trend of UAN < NON < NHN < CON (Table 2).

Compared with other N fertilizer forms (NON, NHN, and CON), UAN application significantly reduced the net N surplus and N balance of winter wheat by 24.18–45.70% and 25.64–55.82%, respectively ($p < 0.05$).

Table 2. Effects of different N fertilizer forms on N balance of winter wheat from 2022 to 2024.

Year	N Flow	CK	NON	NHN	CON	UAN
2022–2023	N input (kg·N·ha^{-1})					
	Fertilizer N	0	180	180	180	180
	Atmospheric N deposition	45.46	45.41	45.57	45.20	45.59
	Seed N content	2.25	2.25	2.25	2.25	2.25
	Non-symbiotic N fixation	15	15	15	15	15
	Total N input	62.71	242.66	242.82	242.45	242.84
	N output (kg·N·ha^{-1})					
	Harvested N removal	89.37	194.51	179.35	175.28	206.37
	Ammonia volatilization N loss	5.09	14.70	15.24	16.23	14.72
	Nitrous oxide N loss	1.54	3.72	3.56	3.69	3.14
	N gas emissions	5.38	13.04	12.44	12.92	11.00
	N leaching	0.69	3.90	3.33	3.61	3.20
	Total N output	102.06 d	229.88 b	213.92 c	211.74 c	238.42 a
	Soil total N variations (kg·N·ha^{-1})	−12.69 b	−11.63 ab	−12.38 ab	−14.29 c	−11.25 a
	Net N surplus (kg·N·ha^{-1})	−26.66 e	48.15 c	63.47 b	67.17 a	36.47 d
	N balance (kg·N·ha^{-1})	−32.66 e	24.41 c	41.28 b	45.01 a	15.67 d
2023–2024	N input (kg·N·ha^{-1})					
	Fertilizer N	0	180	180	180	180
	Atmospheric N deposition	45.38	45.62	45.40	45.24	45.35
	Seed N content	2.18	2.18	2.18	2.18	2.18
	Non-symbiotic N fixation	15	15	15	15	15
	Total N input	62.56	242.80	242.58	242.42	242.53
	N output (kg·N·ha^{-1})					
	Harvested N removal	76.58	184.56	177.36	172.92	198.37
	Ammonia volatilization N loss	5.59	17.86	18.64	19.48	18.26
	Nitrous oxide N loss	1.43	3.92	3.75	3.88	3.36
	N gas emissions	5.01	13.72	13.13	13.58	11.77
	N leaching	0.59	3.77	3.18	3.57	3.27
	Total N output	89.20 d	223.84 b	216.06 c	213.42 c	235.03 a
	Soil total N variations (kg·N·ha^{-1})	−10.37 b	−9.24 a	−10.53 b	−13.81 c	−8.61 a
	Net N surplus (kg·N·ha^{-1})	−14.02 e	58.24 c	65.22 b	69.50 a	44.16 d
	N balance (kg·N·ha^{-1})	−22.27 e	28.20 c	37.04 b	42.81 a	16.11 d

Lowercase letters within the same column indicate significant differences among different N fertilizer treatments in the same winter wheat growing season at the $p = 0.05$ (n = 4) level.

3.6. Correlation Analysis

Cumulative N_2O emissions during the winter wheat growing season were significantly negatively correlated with soil NO_3^--N at maturity, dry matter, LAI, NUE, and yield while showing a significant positive correlation with N balance (Figure 8, $p < 0.05$). Yield was significantly positively correlated with soil NO_3^--N at the jointing and booting stages ($p < 0.05$) and highly positively correlated with soil NO_3^--N at maturity ($p < 0.01$). Yield was significantly negatively correlated with soil NH_4^+-N at the booting stage and N balance ($p < 0.05$), and highly negatively correlated with soil NH_4^+-N at anthesis ($p < 0.01$).

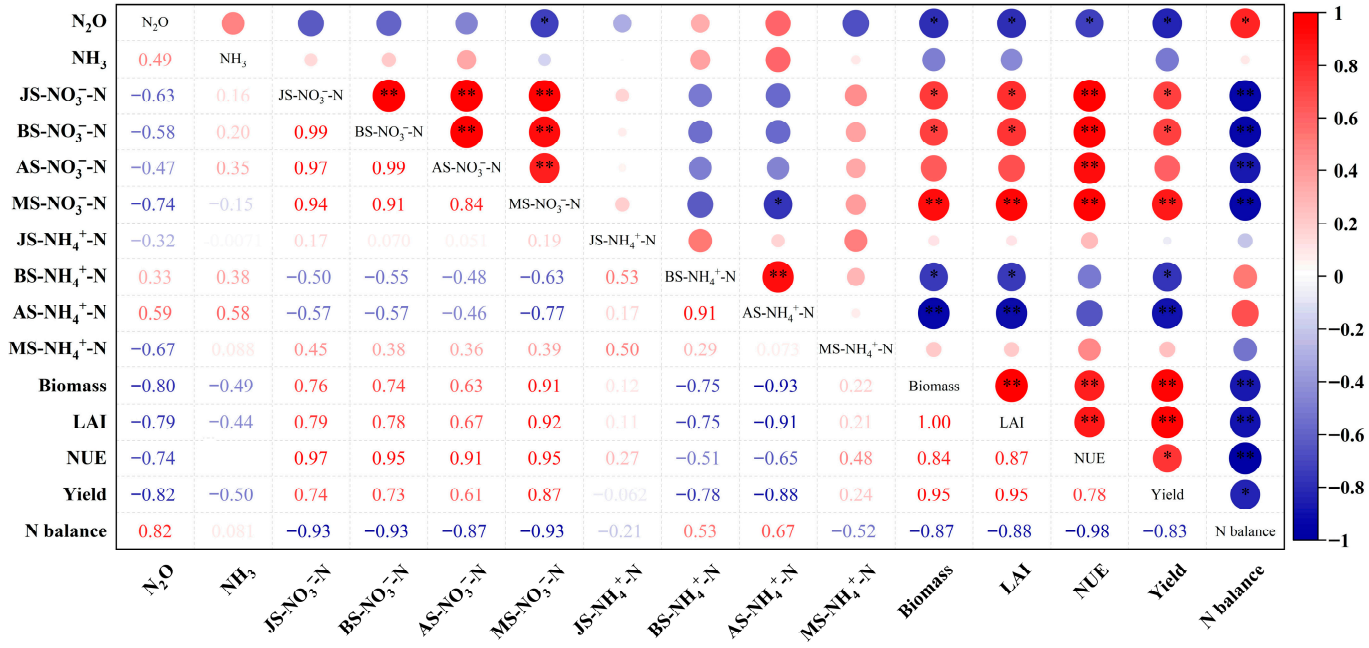


Figure 8. Correlation coefficients between N_2O emissions, NH_3 emissions, soil NO_3^--N and NH_4^+-N at different growth stages of winter wheat, dry matter accumulation, LAI, NUE, and winter wheat yield and N balance. N_2O: cumulative N_2O emissions; NH_3: cumulative NH_3 emissions; JS-NO_3^--N: soil NO_3^--N content at the jointing stage; BS-NO_3^--N: soil NO_3^--N content at the booting stage; AS-NO_3^--N: soil NO_3^--N content at the anthesis stage; MS-NO_3^--N: soil NO_3^--N content at maturity; JS-NH_4^+-N: soil NH_4^+-N content at the jointing stage; BS-NH_4^+-N: soil NH_4^+-N content at the booting stage; AS-NH_4^+-N: soil NH_4^+-N content at the anthesis stage; MS-NH_4^+-N: soil NH_4^+-N content at maturity; Biomass: dry matter; LAI: leaf area index; NUE: N use efficiency. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$.

4. Discussion

4.1. N_2O Fluxes and NH_3 Volatilization Under Different N Fertilizer Forms in Winter Wheat Fields

N_2O emissions from agricultural soils contribute to stratospheric ozone depletion and global warming [37]. In this study, we found that N_2O fluxes in winter wheat fields increased sharply following N fertilizer application and were further increased when irrigation was applied simultaneously with topdressing (Figure 5). Similarly, Lang et al. [13] reported that N_2O fluxes peaked during the initial stages of field wetting by rainfall or irrigation, leading to substantial cumulative emissions. This phenomenon can be attributed to increased soil moisture filling soil pores, which creates anaerobic conditions conducive to denitrifying bacteria, thereby promoting the reduction of soil nitrate to N_2O [38]. Moreover, our results showed that the peak N_2O flux occurred earliest under NON and UAN treatments, followed by NHN and then CON (Figure 5). This pattern is likely related to the transformation processes of urea-based fertilizers: $CO(NH_2)_2$ first hydrolyzes under soil

urease activity to form ammonium carbonate and bicarbonate, which are further decomposed into NH_4^+. The NH_4^+ ions are subsequently oxidized to nitrite by Nitrosomonas and then to nitrate by Nitrobacter [39]. Therefore, multiple factors such as soil pH and microbial activity jointly influence N_2O fluxes following fertilization [40]. This study found that the cumulative N_2O emissions during the winter wheat growing season were significantly reduced under UAN application compared with NON, NHN, and CON treatments, while the soil NO_3^--N residue at maturity was significantly increased (Figures 4 and 5; $p < 0.05$). Two possible mechanisms may explain this reduction. First, UAN may inhibit the activities of nitrate reductase and nitrite reductase while enhancing hydroxylamine reductase activity [41]. Second, the NH_4^+ in UAN is partly adsorbed by soil colloids and partly absorbed by wheat roots, while the NO_3^- is largely assimilated and stored in leaf cells [42]. These processes ultimately reduce N_2O generation. In addition, UAN application significantly increased soil NO_3^--N residues at maturity compared with other N fertilizer forms (Figure 4; $p < 0.05$). This can be attributed to the adsorption of NH_4^+ from UAN by soil colloids, followed by gradual nitrification to NO_3^-, which continuously supplies N for wheat growth [43]. Overall, UAN application effectively mitigated N_2O emissions while enhancing soil NO_3^--N availability, supporting sustainable winter wheat production.

After fertilization, the concentration of soil NH_4^+ increased sharply, leading to high NH_3 volatilization, which can account for more than 30% of applied N loss [44]. In this study, NH_3 volatilization peaked 4–6 days after fertilization under different N fertilizer forms, with higher peaks following topdressing at the jointing stage than those observed after basal fertilization (Figure 6). However, the overall NH_3 volatilization measured in this trial was relatively low (Table 2), likely because supplementary irrigation during topdressing raised soil water content to 80%. Previous studies have shown that N loss decreases with increasing irrigation, and maintaining soil water at 70–80% effectively enhances water use efficiency and reduces gaseous losses from winter wheat fields [22]. Moreover, we observed that UAN application significantly reduced cumulative NH_3 volatilization by 2.04–9.33% compared with NHN and CON, although differences from NON were not significant (Figure 6; $p < 0.05$). This reduction can be explained by the rapid urease hydrolysis of urea in CON ($CO(NH_2)_2 + 3H_2O \rightarrow CO_2 + 2NH_3 + 2H_2O$), which produces large amounts of NH_3 [45], and the reversible reaction between NH_4^+ and OH^- in NHN that increases NH_3 volatilization when soil NH_4^+ is abundant. Appropriate irrigation mitigates this effect by suppressing NH_3 emissions [46].

4.2. Yield and NUE Under Different N Fertilizer Forms in Winter Wheat

Rational application of N fertilizer is a crucial strategy to ensure high wheat yields, reduce costs, and minimize environmental pollution. In this study, application of UAN significantly increased the number of spikes and grains per spike during the winter wheat growing season compared with other N fertilizer forms, thereby enhancing grain yield (Table 1; $p < 0.05$). The superior performance of UAN can be attributed to its ability to meet the preference of winter wheat for NO_3^--N while simultaneously reducing the risk of excessive NO_3^--N leaching. Nitrates and nitrites in the soil suppress nitrification, and the persistent nitrification inhibition effect of UAN significantly increased soil NH_4^+-N accumulation, thereby improving NUE and yield [17], which is consistent with the findings of Brodowska et al. [46]. Previous studies have also demonstrated that N fertilizer form significantly influences spike number, and that spikelet number and thousand-kernel weight are the key yield determinants in ammonium nitrate fertilization [47]. However, Hussain et al. [48] reported that amide N fertilizer significantly increased wheat yield compared with nitrate, ammonium, and ammonium nitrate fertilizers, which contrasts with our results. A possible explanation lies in the experimental conditions: in our study,

topdressing was applied via drip fertigation at the jointing stage. Before hydrolysis, only about 20% of amide N can be adsorbed by soil colloids, and irrigation during topdressing reduced soil temperature, thereby decreasing urease activity [49]. Consequently, amide N fertilizer could not provide sufficient N during the critical demand stages of winter wheat, resulting in reduced yield.

In this study, application of UAN increased the LAI and biomass accumulation at maturity compared with NON, NHN, and CON (Figure 7; $p < 0.05$). Maintaining higher post-anthesis biomass accumulation is recognized as a key pathway for increasing wheat yield, and both N application rate and fertilizer form exert significant regulatory effects on biomass accumulation and translocation [50]. Our results further demonstrated that soil NO_3^--N content at the jointing and booting stages was significantly and positively correlated with yield ($p < 0.05$), while NO_3^--N content at maturity was extremely significantly and positively correlated with yield (Figure 8; $p < 0.01$). The mechanism behind this lies in the properties of UAN: NH_4^+-N is readily adsorbed onto soil colloids in the surface layer and subsequently nitrified, thereby ensuring N availability for later growth stages; meanwhile, NO_3^--N moves moderately downward after application, enabling the deeper roots of winter wheat to access N [46]. In contrast, soil NH_4^+-N content at the booting stage showed a significant negative correlation with yield ($p < 0.05$), and at the anthesis stage showed an extremely significant negative correlation with yield ($p < 0.01$). This can be explained by the fact that NH_4^+-N tends to bind strongly to soil particles and remains concentrated in the surface plow layer, where it cannot be effectively absorbed by the deeper root system. Furthermore, excessive NH_4^+-N accumulation around the roots after the jointing stage can lead to ammonium toxicity, inhibiting root respiration and the uptake of other ions, thereby restricting aboveground growth [51].

In this study, application of UAN significantly increased the NHI and NUE compared with NON, NHN, and CON (Figure 7; Table 1; $p < 0.05$). Moreover, NUE showed an extremely significant positive correlation with soil NO_3^--N concentrations at the jointing, booting, anthesis, and maturity stages (Figure 8; $p < 0.01$). After the jointing stage, which is a critical period for yield formation, a sufficient but balanced supply of N in the soil is essential. UAN contributes to this by enabling moderate downward movement of NO_3^--N under irrigation, which increased NO_3^--N availability in the 80–100 cm soil layer (Figure 3). Simultaneously, irrigation enhanced soil moisture, promoting nitrification and accelerating the conversion of NH_4^+-N in the surface soil into NO_3^--N, at which point wheat reaches its peak efficiency in NO_3^--N uptake [52].

4.3. N Balance Under Different N Fertilizer Forms in Winter Wheat

N balance refers to the relationship (difference) between N inputs and N outputs within a given system (agroecosystem) over a defined period, and it serves as an important indicator for N management and policy making [53]. N balance reflects either soil N surplus (N input > N output) or N deficit (N input < N output) per unit of cultivated land. In this study, fertilizer application was identified as the main source of N input, accounting for 77.50–77.53% of total N inputs, while harvested N removal contributed 82.40–87.73% of total N outputs (Table 2). Generally, fertilizer N is lost in the forms of NH_3 volatilization, N_2O emissions, runoff, or leaching, which can cause severe environmental problems. Among these, N leaching may lead to groundwater pollution, soil acidification, reduced soil quality, and impaired crop production [54]. In this experiment, the NO_3^--N, NH_4^+-N, and $CONH_2$-N supplied by UAN exhibited spatiotemporal distribution differences that matched the temporal and spatial patterns of N uptake by winter wheat. This balanced the soil N supply with crop N demand, promoted efficient N utilization, and reduced N losses through N_2O emissions (Figure 5), NH_3 volatilization, and NO_3^--N leaching (Figure 6;

$p < 0.05$). Our results showed that application of UAN significantly decreased net N surplus and N balance compared with other fertilizer forms (NON, NHN, and CON) ($p < 0.05$), respectively. Compared with single-form N fertilizers, UAN markedly enhanced crop N uptake efficiency, reduced net N surplus, effectively lowered gaseous N losses (N_2O and NH_3) that contribute to environmental impacts, and maintained relatively low soil residual NO_3^--N concentrations, thereby sustaining field N balance to the greatest extent [55].

Soil moisture serves as the carrier through which fertilizer N enters the N cycle of winter wheat fields. When soil water content is high, NO_3^--N in the soil profile tends to migrate downward with water movement. Improper irrigation combined with excessive precipitation can transport inorganic N into deeper soil layers, thereby exacerbating NO_3^--N leaching [56]. This process reduces the N supply capacity of the root zone, subjects root growth to nutrient stress, restricts N uptake by crops [57], and ultimately leads to higher net N surplus. On the other hand, although increased soil moisture reduces soil aeration and thus minimizes NH_3 volatilization and associated environmental pollution, the downward movement of NO_3^--N increases the soil N surplus, which is unfavorable for maintaining N balance in wheat fields [58]. In the present study, however, supplementary irrigation based on soil moisture monitoring effectively reduced gaseous N losses while ensuring crop N uptake, thereby lowering net N surplus, sustaining N balance in the field, and improving N resource utilization efficiency within the agroecosystem. Furthermore, winter wheat is a deep-rooted crop with a nutrient uptake depth of up to 200 cm, and NO_3^--N leached below the root zone (120–200 cm) after the previous wheat harvest can support the growth of the subsequent crop [59]. Application of UAN under irrigation conditions promoted moderate downward movement of NO_3^--N, facilitating N uptake and yield formation.

5. Conclusions

The results of this study confirmed our hypothesis that, compared with single-form nitrogen fertilizers (nitrate, ammonium, or amide), the compound-form urea ammonium nitrate (UAN) more effectively improved the leaf area index and biomass accumulation of winter wheat, thereby enhancing yield and nitrogen use efficiency. Meanwhile, UAN application reduced gaseous nitrogen emissions from the farmland ecosystem and significantly decreased both net nitrogen surplus and nitrogen balance. Therefore, integrating high-yield cultivation practices with water–fertilizer management and UAN application provides a feasible strategy for achieving high-yield, high-efficiency, and environmentally sustainable winter wheat production in northern China and similar agroecological regions. However, the large-scale implementation of UAN under water–fertilizer integration systems may be limited by factors such as cost, management complexity, and regional variability in irrigation infrastructure. Future studies should evaluate the economic feasibility and long-term environmental impacts of this practice and explore the combined use of UAN with liquid organic fertilizers or nitrogen stabilizers to further enhance winter wheat productivity and nitrogen balance within agroecosystems.

Author Contributions: R.H.: Writing—original draft, Data curation, Validation, Software, Investigation, Visualization; J.M.: Investigation; X.X.: Investigation; Q.H.: Investigation; Y.W.: Investigation; W.Z.: Investigation; P.W.: Resources, Methodology; A.R.: Investigation; Z.G.: Investigation; R.G.: Methodology, funding acquisition, Writing—review and editing; M.S.: Methodology, funding acquisition, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Project of Shanxi Province key lab construction (Z135050009017-3-3), the China Agriculture Research System (CARS-03-01-24), the 2023 Annual Science and Technology Innovation Projects of Shanxi National Agricultural High-Tech Zone (Taigu

National Science and Technology Innovation Center), the Key Laboratory of Crop Ecology and Water and Fertilizer Efficient Utilization in Shanxi Province, the technology innovation team of Shanxi Province, the "Sanjin Yingcai" Physiology of Drought-Resistant Wheat Cultivation" Shanxi Science and Technology Innovation Team.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NON	Nitrate N fertilizer
NHN	Ammonium N fertilizer
CON	Amide N fertilizer
UAN	Urea ammonium nitrate
CK	Control
WUE	Water use efficiency
N	Nitrogen
NUE	Nitrogen use efficiency
N_2O	Nitrous oxide
NH_3	Ammonia
NO_3^--N	Nitrate
NH_4^+-N	Ammonium
LAI	Leaf area index
HI	Harvest index
NHI	Nitrogen harvest index
LSD	Least significant difference

References

1. Wang, H.; Wu, J.; Li, G.; Yuan, J. Influence of Nitrogen Addition Levels on N_2O Flux and Yield of Spring Wheat in the Loess Plateau. *Agronomy* **2025**, *15*, 1377. [CrossRef]
2. Tong, J.; Xiong, Y.; Lu, Y.; Li, W.; Lin, W.; Xue, J.; Sun, M.; Wang, Y.; Gao, Z. Drip Fertigation Enhances the Responses of Grain Yield and Quality to Nitrogen Topdressing Rate in Irrigated Winter Wheat in North China. *Plants* **2024**, *13*, 1439. [CrossRef]
3. Yu, Y.; Liu, Z.; Zhang, Y.; Su, Z.; Jian, H.; Gao, J.; Hartmann, R.; Gabriels, D. Yield of winter wheat in the Chinese Loess Plateau depends strongly on precipitation seasonality. *Sci. Rep.* **2025**, *15*, 5344.
4. Tong, J.; Xiong, Y.; Lu, Y.; Li, W.; Xue, J.; Sun, M.; Wang, Y.; Gao, Z. Drip fertigation enhances the responses of grain yield, nitrogen and water use efficiency, and quality of irrigated winter wheat in northern China to nitrogen application. *Front. Plant Sci.* **2024**, *15*, 1372385.
5. Lu, J.; Hu, T.; Geng, C.; Cui, X.; Fan, J.; Zhang, F. Response of yield, yield components and water–nitrogen use efficiency of winter wheat to different drip fertigation regimes in Northwest China. *Agric. Water Manag.* **2021**, *255*, 107034. [CrossRef]
6. Li, H.; Mei, X.; Nangia, V.; Guo, R.; Liu, Y.; Hao, W.; Wang, J. Effects of different nitrogen fertilizers on the yield, water-and nitrogen-use efficiencies of drip-fertigated wheat and maize in the North China Plain. *Agric. Water Manag.* **2021**, *243*, 106474. [CrossRef]
7. Recous, S.; Machet, J.M.; Mary, B. The fate of labelled15N urea and ammonium nitrate applied to a winter wheat crop: II. plant uptake and N efficiency. *Plant Soil* **1988**, *112*, 215–224. [CrossRef]
8. Li, H.; Mei, X.; Wang, J.; Huang, F.; Hao, W.; Li, B. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. *Agric. Water Manag.* **2021**, *244*, 106534. [CrossRef]
9. Govindasamy, P.; Muthusamy, S.K.; Bagavathiannan, M.; Mowrer, J.; Jagannadham, P.; Maity, A.; Halli, H.; Sujayanand, G.; Vadivel, R.; Das, T.; et al. Nitrogen use efficiency—A key to enhance crop productivity under a changing climate. *Front. Plant Sci.* **2023**, *14*, 1121073. [CrossRef]

10. Zhai, W.; Cheng, Q.; Duan, F.; Huang, X.; Chen, Z. Remote sensing-based analysis of yield and water-fertilizer use efficiency in winter wheat management. *Agric. Water Manag.* **2025**, *311*, 109390. [CrossRef]
11. Wang, S.; Wang, D.; Liu, T.; Liu, Y.; Luo, M.; Li, Y.; Zhou, W.; Yang, M.; Liang, S.; Li, K. Simulation of winter wheat growth dynamics and optimization of water and nitrogen application systems based on the aquacrop model. *Agronomy* **2024**, *14*, 110. [CrossRef]
12. Shi, C.; Liao, A.; Du, C.; Li, L.; Wan, X.; Liu, Y. Optimal Effect of Substituting Organic Fertilizer for Inorganic Nitrogen on Yield and Quality of Winter Wheat under Drip Irrigation. *Agronomy* **2024**, *14*, 2012. [CrossRef]
13. Lang, Y.; Wu, Y.; Bao, H.; Tuya, N.; Liu, F.; Ruhan, A.; Wu, X.; Yang, J.; Qi, L.; Wang, X. Seasonal variation of N_2O flux at the water air interface and its influencing factors in the Inner Mongolia section of the Yellow River in 2023. *J. Freshw. Ecol.* **2025**, *40*, 2501974. [CrossRef]
14. Gao, W.; Wang, X.; Jian, Z.; Chen, Y.; Ni, X.; Wang, J.; Dong, Y.; Li, Z.; Cao, B. Effects of Controlled-release Blended Fertilizer on Crop Yield and Greenhouse Gas Emissions in Wheat-maize Rotation System. *Huan Jing Ke Xue Huanjing Kexue* **2024**, *45*, 2891–2904.
15. Seçer, M.; Elmaci, Ö.L.; Erdemir, O. Does the ammonium fixation capacity of soils have a significant effect on the nitrogen nutrition of wheat? *Commun. Soil Sci. Plant Anal.* **2011**, *42*, 1606–1618. [CrossRef]
16. Bilge, U.; Çimrin, K.M. The effect of top dressing fertilizer forms applied at different periods on yield and some yield components in durum wheat varieties. *Mustafa Kemal Üniversitesi Tarım Bilim. Derg.* **2025**, *30*, 13–34. [CrossRef]
17. Guo, C.; Wang, H.; Zou, D.; Wang, Y.; Han, X. A novel amended nitrification inhibitor confers an enhanced suppression role in the nitrification of ammonium in soil. *J. Soils Sediments* **2022**, *22*, 831–843. [CrossRef]
18. Ramírez, G.B.; Miguel, C.; Montanha, G.S.; Carmona, F.J.; Dal Sasso, G.; Sillero, J.C.; Skov Pedersen, J.; Masciocchi, N.; Guagliardi, A.; Pérez-de-Luque, A. Reducing nitrogen dosage in Triticum durum plants with urea-doped nanofertilizers. *Nanomaterials* **2020**, *10*, 1043. [CrossRef] [PubMed]
19. Si, Z.; Zain, M.; Li, S.; Liu, J.; Liang, Y.; Gao, Y.; Duan, A. Optimizing nitrogen application for drip-irrigated winter wheat using the DSSAT-CERES-Wheat model. *Agric. Water Manag.* **2021**, *244*, 106592. [CrossRef]
20. Winkhart, F.; Schmid, H.; Hülsbergen, K.J. Effects of biogas digestate on winter wheat yield, nitrogen balance, and nitrous oxide emissions under organic farming conditions. *Agronomy* **2024**, *14*, 1739. [CrossRef]
21. Wang, H.; Ma, S.; Shao, G.; Dittert, K. Use of urease and nitrification inhibitors to decrease yield-scaled N_2O emissions from winter wheat and oilseed rape fields: A two-year field experiment. *Agric. Ecosyst. Environ.* **2021**, *319*, 107552. [CrossRef]
22. Fu, Y.; Cui, Z.; Yao, J.; Ji, F.; Lu, W.; He, Z. Effects of water and nitrogen coupling on photosynthetic characteristics and yield of winter wheat in film hole irrigation fields. *Desalination Water Treat.* **2022**, *268*, 273–284. [CrossRef]
23. Liu, X.; Liu, J.; Huang, C.; Liu, H.; Meng, Y.; Chen, S.; Ma, S.; Liu, Z. The impacts of irrigation methods and regimes on the water and nitrogen utilization efficiency in subsoiling wheat fields. *Agric. Water Manag.* **2024**, *295*, 108765. [CrossRef]
24. Liu, Z.; Li, Z.; Huang, F.; Wang, B.; Zhao, C.; Zhang, P.; Jia, Z. Plastic film mulching and biochar amendment enhance maize yield and nitrogen fertilizer use efficiency by reducing gaseous nitrogen losses. *Field Crops Res.* **2022**, *289*, 108714. [CrossRef]
25. Stella, P.; Loubet, B.; Laville, P.; Lamaud, E.; Cazaunau, M.; Laufs, S.; Bernard, F.; Grosselin, B.; Mascher, N.; Kurtenbach, R.; et al. Comparison of methods for the determination of NO-O_3-NO_2 fluxes and chemical interactions over a bare soil. *Atmos. Meas. Tech.* **2012**, *5*, 1241–1257. [CrossRef]
26. Frame, W.H.; Alley, M.M.; Whitehurst, G.B.; Whitehurst, B.M.; Campbell, R.G. In vitro evaluation of coatings to control ammonia volatilization from surface-applied urea. *Agron. J.* **2012**, *104*, 1201–1207. [CrossRef]
27. *GB 1351-2023*; Wheat. State Administration for Market Regulation National Standardization Administration: Beijing, China, 2023.
28. Tao, Z.; Tao, L.; Cao, F.; Chen, J.; Yin, X.; Liang, T.; Huang, M. Contrasting characteristics of lodging resistance in two super-rice hybrids differing in harvest index. *Phyton* **2022**, *91*, 429. [CrossRef]
29. Haile, D.; Nigussie, D.; Ayana, A. Nitrogen use efficiency of bread wheat: Effects of nitrogen rate and time of application. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 389–410. [CrossRef]
30. Liu, Z.; Gao, J.; Gao, F.; Dong, S.; Liu, P.; Zhao, B.; Zhang, J. Integrated agronomic practices management improve yield and nitrogen balance in double cropping of winter wheat-summer maize. *Field Crops Res.* **2018**, *221*, 196–206. [CrossRef]
31. Gao, Q.; Zhang, X.; Liu, L.; Lu, X.; Wang, Y. A database of atmospheric inorganic nitrogen deposition fluxes in China from satellite monitoring. *Sci. Data* **2023**, *10*, 698. [CrossRef]
32. Guo, D.; Wang, R.; Chen, C.; Yin, B.; Ding, Z.; Wang, X.; Zhao, M.; Zhou, B. Nitrogen supply mitigates heat stress on photosynthesis of maize (*Zea mays* L.) during early grain filling by improving nitrogen assimilation. *J. Agron. Crop Sci.* **2024**, *210*, e12750. [CrossRef]
33. Li, W.; Yao, L.; Long, M.; Zhang, H.; Zhang, Y.; Wen, X.; Mo, F.; Han, J.; Liao, Y. Biochar reduced soil N losses and improved N balance in a rainfed winter-wheat cropping agroecosystem. *Appl. Soil Ecol.* **2022**, *179*, 104591. [CrossRef]

34. Huang, M.; Liang, T.; Ou-Yang, Z.; Wang, L.; Zhang, C.; Zhou, C. Leaching losses of nitrate nitrogen and dissolved organic nitrogen from a yearly two crops system, wheat-maize, under monsoon situations. *Nutr. Cycl. Agroecosystems* **2011**, *91*, 77–89. [CrossRef]
35. Galloway, J.N.; Winiwarter, W.; Leip, A.; Leach, A.M.; Bleeker, A.; Erisman, J.W. Nitrogen footprints: Past, present and future. *Environ. Res. Lett.* **2014**, *9*, 115003. [CrossRef]
36. Tian, Z.; Ge, Y.; Zhu, Q.; Yu, J.; Zhou, Q.; Cai, J.; Jiang, D.; Cao, W.; Dai, T.B. Soil nitrogen balance and nitrogen utilization of winter wheat affected by straw management and nitrogen application in the Yangtze river basin of China. *Arch. Agron. Soil Sci.* **2019**, *65*, 1–15. [CrossRef]
37. Wang, X.; Xiang, B.; Li, J.; Zhang, M. Using adaptive and aggressive N_2O-reducing bacteria to augment digestate fertilizer for mitigating N_2O emissions from agricultural soils. *Sci. Total Environ.* **2023**, *903*, 166284. [CrossRef]
38. Rubin, R.L.; Ballantine, K.A.; Hegberg, A.; Andras, J.P. Flooding and ecological restoration promote wetland microbial communities and soil functions on former cranberry farmland. *PLoS ONE* **2021**, *16*, e0260933. [CrossRef]
39. Berendt, J.; Wrage-Mönnig, N. Denitrification is not necessarily the main source of N_2O from rewetted fens. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 3705–3713. [CrossRef]
40. Yuan, J.; Yao, Y.; Guan, Y.; Sadiq, M.; Li, J.; Liu, S.; Lu, Y.; Xu, G.; Du, M.; Li, G.; et al. Effects of land use patterns on soil properties and nitrous oxide flux on a semi-arid environmental conditions of Loess Plateau China. *Glob. Ecol. Conserv.* **2024**, *51*, e02899. [CrossRef]
41. Pu, Y.; Zhu, B.; Dong, Z.; Liu, Y.; Wang, C.; Ye, C. Soil N_2O and NO_x emissions are directly linked with N-cycling enzymatic activities. *Appl. Soil Ecol.* **2019**, *139*, 15–24. [CrossRef]
42. Shi, W.; Bian, R.; Li, L.; Lian, W.; Liu, X.; Zheng, J.; Chen, K.; Zhang, X.; Drosos, M.; Joseph, S.; et al. Assessing the impacts of biochar-blended urea on nitrogen use efficiency and soil retention in wheat production. *GCB Bioenergy* **2022**, *14*, 65–83. [CrossRef]
43. Ratajczak, K.; Becher, M.; Kalembasa, S.; Sulewska, H. Quantitative determination of nitrogen fixed by soybean and its uptake by winter wheat as aftercrops within sustainable agricultural systems. *Sustainability* **2024**, *16*, 10153. [CrossRef]
44. Chen, T.; Cui, E.; Sun, K.; Hu, C.; Li, S.; Li, P.; Zhao, Z.; Liu, C.; Cui, B.; Fan, X. Multiple Nitrogen Sources Application Inhibits Increasing Ammonia Volatilization Under Reducing Irrigation. *Agronomy* **2024**, *14*, 2927. [CrossRef]
45. Peng, L.; Tao, L.; Ma, S.; Wang, X.; Wang, R.; Tu, Y.; Wang, L.; Ti, C.; Yan, X. ^{15}N natural abundance characteristics of ammonia volatilization from soils applied by different types of fertilizer. *Atmosphere* **2022**, *13*, 1566. [CrossRef]
46. Brodowska, M.S.; Wyszkowski, M.; Karsznia, M. Application of urea and ammonium nitrate solution with potassium thiosulfate as a factor determining macroelement contents in plants. *Agronomy* **2024**, *14*, 1097. [CrossRef]
47. Popov, Y.V.; Avramenko, S.V. Effect of autumn application of different doses and types of nitrogen fertilizer on post-sunflower-sown winter wheat yield. *Sel. I Nasinn.* **2024**, *125*, 94–101.
48. Hussain, A.; Azeem, N.; Riaz, T.; Khan, T.Y.; Pehlwan, B.; Amjad, T.; Muzammal, M.; Sani, I.; Habiba, U.; Sarfraz, B. Impact of Various Nitrogenous Fertilizers on Wheat Crop Yield and Growth. *Indus J. Biosci. Res.* **2025**, *3*, 364–369. [CrossRef]
49. Yuan, J.; Sadiq, M.; Rahim, N.; Li, G.; Yan, L.; Wu, J.; Xu, G. Tillage strategy and nitrogen fertilization methods influences on selected soil quality indicators and spring wheat yield under semi-arid environmental conditions of the loess plateau, China. *Appl. Sci.* **2022**, *12*, 1101. [CrossRef]
50. Zhang, D.; Hao, X.; Fan, Z.; Hu, X.; Ma, J.; Guo, Y.; Wu, L. Optimizing tillage and fertilization patterns to improve soil physical properties, NUE and economic benefits of wheat-maize crop rotation systems. *Agriculture* **2022**, *12*, 1264. [CrossRef]
51. Chhabra, V.; Sreethu, S.; Kaur, G. Wheat growth and yield in the rice-wheat cropping system: Impact of crop establishment techniques, sowing schedule and nitrogen management. *Int. J. Plant Prod.* **2024**, *18*, 453–464. [CrossRef]
52. Abdelhamied, A.S.; Selim, E.M.M.; Mosaad, I.S.M. Modified Slow-Release Urea Fertilizers on Yield and Nitrogen Use Efficiency of Wheat Crop (*Triticum aestivum* L.) for Safe and Sustainable Agricultural System. *Commun. Soil Sci. Plant Anal.* **2024**, *55*, 3497–3509. [CrossRef]
53. Li, C.; Shi, Y.; Yu, Z.; Zhang, Y.; Zhang, Z. Reducing nitrogen application under water saving irrigation reduces greenhouse gas emissions by regulating the population of functional microorganisms, compatible with improving the wheat yield in the North China Plain. *Plant Soil* **2025**. [CrossRef]
54. Wang, J.; Qian, R.; Li, J.; Wei, F.; Ma, Z.; Gao, S.; Sun, X.; Zhang, P.; Cai, T.; Zhao, X.; et al. Nitrogen reduction enhances crop productivity, decreases soil nitrogen loss and optimize its balance in wheat-maize cropping area of the Loess Plateau, China. *Eur. J. Agron.* **2024**, *161*, 127352. [CrossRef]
55. Tong, B.; Hou, Y.; Wang, S.; Ma, W. Partial substitution of urea fertilizers by manure increases crop yield and nitrogen use efficiency of a wheat–maize double cropping system. *Nutr. Cycl. Agroecosystems* **2023**, *127*, 11–21. [CrossRef]
56. Yang, Y.; Qin, Q.; Li, Q.; Nangia, V.; Lan, B.; Mo, F.; Liao, Y.; Liu, Y. Effect of nitrogen management on wheat yield, water and nitrogen utilization, and economic benefits under ridge-furrow cropping system with supplementary irrigation. *Agronomy* **2023**, *13*, 1708. [CrossRef]

57. Hagn, L.; Mittermayer, M.; Kern, A.; Kimmelmann, S.; Maidl, F. Effects of sensor-based, site-specific nitrogen fertilizer application on crop yield, nitrogen balance, and nitrogen efficiency. *Sensors* **2025**, *25*, 795. [CrossRef] [PubMed]
58. Chen, Y.; Zhao, N.; Hao, Y.; Li, X.; Fan, M.; Shi, X.; Jia, L. Optimizing nutrient inputs by balancing spring wheat yield and environmental effects in the Hetao Irrigation District of China. *Sci. Rep.* **2022**, *12*, 22524. [CrossRef]
59. Andrzejewska, A.; Przygocka-Cyna, K.; Grzebisz, W. Balanced Fertilization of Winter Wheat with Potassium and Magnesium—An Effective Way to Manage Fertilizer Nitrogen Sustainably. *Sustainability* **2025**, *17*, 6705. [CrossRef]

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