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The Application of Controlled Release Urea Mitigates Reactive Nitrogen Losses and Optimizes Nitrogen Management of Summer Maize: A Case Study in the North China Plain

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Abstract:

In response to the critical challenges of low nitrogen use efficiency (NUE) and elevated environmental risks in the intensive agricultural systems of the North China Plain (NCP) in China, this study conducted a two-year field experiment to investigate the spatial-temporal synchronization between nutrient release from controlled-release urea (CRU) and N uptake (Nuptake) by summer maize, as well as the multi-scale regulatory mechanisms underlying its environmental impacts. Three treatments were implemented: no N application (CK), split applications of conventional urea at a rate of 180 kg N/ha (U), and a single basal application of CRU at an equivalent N rate to U (CRU). By integrating in situ gas monitoring, soil profile N flux analysis, and an economic-environmental benefit assessment framework, this study systematically elucidates the regulatory mechanisms and environmental implications of CRU on the N cycle within the soil–crop system.

The results demonstrated that, the CRU treatment increased maize yield by 8.0% ($P < 0.01$) compared to the U treatment, with partial factor productivity of N (PFPN) and N agronomic efficiency (NAE) improving by 8.0% and 34.2%, respectively, and it has increased the economic benefits by 12.7%. Notably, compared with U, CRU significantly reduced ammonia volatilization (AV) by 57.4% and 54.4% during the basal fertilization and topdressing periods, respectively. Over the entire maize growing season, CRU decreased N_2O emissions by 68.8%, while apparent N loss was reduced by 35.5%. N uptake by maize during the late growth stage increased by 9.9% under CRU relative to U. Furthermore, CRU treatment improved the distribution of mineral N (Nmin) in the 0–40 cm soil profile, significantly increasing Nmin content in the 0–20 cm and 20–40 cm layers by 65.9% and 71.0%, respectively. Nitrate leaching was reduced by 27.3%, and the N balance surplus declined by 13.0%. In conclusion, through a synergistic mechanism of "nutrient slow release–environmental control–crop efficiency enhancement," CRU application not only supported high maize yields (>12 t/ha) but also reduced the N ecological footprint by 35.5%. This study provides direct evidence that CRU synchronizes N release with crop N uptake, reconstructs soil N profiles, and breaks the synergistic occurrence of ammonia volatilization, N_2O emission, and nitrate leaching. This approach represents a favorable N management strategy for croplands in the NCP, offering a scientific foundation for sustainable and efficient agricultural production in this region.

Keywords: Controlled release fertilizer; Summer maize; N balance; N loss; mineral N;

1 Introduction

The advent of the Haber-Bosch synthetic ammonia technology in the 20th century established chemical N fertilizers as the primary source of N in agricultural production, this advancement significantly enhanced global food production capacity. In China, a country with a large population and limited arable land, the pressure on grain production is substantial (Liu et al., 2025). Xiang et al. (2020) projected that by 2050, China will face a substantial grain deficit. The demand for grain is anticipated to significantly exceed supply, leading to a national grain self-sufficiency rate of only 87.56%, which falls considerably below the internationally recognized threshold for food security. By 2024, China's consumption of chemical N fertilizers for food crop production is projected to account for approximately 25.2% of the global total (Jiang et al., 2023). The amount of chemical fertilizer applied per unit area of land by Chinese farmers is the highest in the world. Among this, the N fertilizer input exceeds 1603 million tons (China Statistical Yearbook, 2024). Currently, the fertilizer utilization rate for the three major food crops in China—rice, wheat, and maize-is 42.6% (Ministry of Agriculture and Rural Affairs, 2024), which is 10-20% lower than that of developed countries in Europe or America (Ministry of Agriculture and Rural Affairs, 2025). Meanwhile, the proportion of reactive N (Nr) loss from farmland in China accounts for as high as 30% to 70% of the total input (Bindraban et al., 2020). Research indicates that N fertilizer plays a crucial role in enhancing crop yields and promoting national economic development. However, the problems associated with excessive and irrational N fertilizer application have become increasingly pronounced (Zhang et al., 2023), resulting in soil quality degradation, environmental pollution, and a decline in crop quality (Li and Wu, 2008).

Duan et al. (2024) quantified the N input and output fluxes within China's farmland system. Their findings indicated that approximately 47.5% of N is currently lost via volatilization, leaching, and runoff pathways. These losses have resulted in greatly reduced fertilizer use efficiency (FUE), while also causing serious environmental negative effects, such as N_2O emissions and mineral N leaching, which contribute to air pollution, global warming and non-point source pollution, and pose threat to human health (Long et al., 2023). To achieve an optimal balance between crop N demand and N supply, promote the green and sustainable development goals, researchers proposed the 4R principle for rational fertilization, which encompasses the right fertilizer source, application rate, timing, and placement (Snyder, 2017). Therefore, based on this principle, implementing scientifically reasonable N fertilizer management strategies-while reducing N application rates-represents a key approach for promoting high agricultural productivity and environmentally sustainable development in China (Xu, 2024). You et al. (2024) conducted a meta-analysis and found that the effectiveness of reducing N loss is mainly influenced by the optimized management measures of farmland. Among them, the creation of novel fertilizers and optimized fertilization techniques (4R management) have great potential to reduce global N loss in farmland. In particular, the application of novel fertilizers has a significant impact on various N loss (N_2O emissions, AV, N runoff, and N leaching), reducing them by an

average of 28-35%. In addition, it is found that the application of novel fertilizers generally led to higher crop yields and improved FUE compared to conventional fertilization. The increase in yield ranged from 4.6% to 17.5%, and the NUE increased by 16.8% to 52.3% (Ding et al., 2023).

Controlled release fertilizers (CRFs), as a type of novel fertilizer, can regulate the release characteristics of the fertilizer, ensuring that the N release matches the N absorption pattern of the crops. This addresses the limitations associated with conventional fertilizers, such as a short efficacy period and a mismatch between nutrient supply and crop demand, which result in low NUE and significant resource waste. Research has demonstrated that single-application fertilization is more time- and labor-efficient compared to the conventional practice of applying fertilizers in multiple doses (Zou et al., 2022). Research has shown that the rational application of CRU in the southwestern region can effectively enhance environmental sustainability by 2.82-4.61%, increase economic benefits by 5.21-11.44%, promote the rapid development of local agricultural products industries, and improve the agricultural environment (Lyu et al., 2021). Furthermore, based on life cycle assessment (LCA), the relevant field experiments on spring maize have shown that the full life cycle carbon footprint under the CRU treatment in Liutsi County, Jilin Province is 28-42% lower than that of ordinary urea, mainly attributed to the reduction in N loss and the increase in carbon sequestration by the crops (Zheng, 2023).

As a primary grain-producing region in China, the NCP plays a crucial role in ensuring national food security. However, intensive agricultural practices in this region have led to increasingly severe issues such as excessive N input and significant environmental pollution. To sustainably increase per capita grain output, the application of CRFs has been identified as an effective strategy to address these challenges (Zhang et al., 2013; Ju and Gu, 2014). Zhang et al. (2017) reported that in a wheat–maize rotation system on the NCP region, the annual N_2O emissions under CRF treatment were 20.60%–33.79% lower than those under conventional farmer fertilization practices, indicating potential for further emission reductions. Furthermore, Zhang et al. (2019) demonstrated through a two-year field experiment that, compared to conventional fertilization, CRFs can maintain stable crop yields even with reduced nitrogen application 14.3%, thereby achieving the dual objectives of fertilizer savings and improved efficiency. Their study also showed that CRFs increase soil Nmin content in the 0–40 cm layer and reduce nitrogen loss by 19.9%. Collectively, existing research indicates that CRFs contribute to both enhanced crop productivity and reduced N losses. Nevertheless, current understanding of the mechanisms underlying soil N migration and transformation under CRF application remains limited, particularly regarding the specific pathways through which CRU mitigates N loss and promotes N uptake in soil.

N balance, as a comprehensive indicator, serves as an effective tool for evaluating the performance of specific N fertilizer management practices. By quantifying the N input–output balance, a more systematic and in-depth understanding of fertilization efficiency and its associated environmental impacts can be achieved. Owing to variations in research objectives and technical

constraints, certain studies have employed simplified N balance methodologies, treating unmeasured N loss pathways as apparent N loss (Liu et al., 2010; Ji et al., 2017). A spring maize field experiment conducted in Ningxia, China, demonstrated that CRU, applied as the primary N source (N: 240–360 kg/ha), resulted in above-ground N uptake by maize being the dominant N output component (N: 172.4–292.7 kg/ha). Compared with conventional fertilization practices, single application of CRFs significantly increased maize yield by 20.0%. Furthermore, residual soil Nmin, apparent N loss, and apparent N surplus rate were reduced by 56.2%, 42.0%, and 49.8%, respectively. These findings indicate that CRFs enhance N uptake and utilization efficiency in spring maize, reduce residual soil Nmin and apparent N losses, and enable N fertilizer savings exceeding 30% in Yongning County, Ningxia (Wang et al., 2025). Considering the unique challenges of N management in cropland systems of the NCP, this study integrates data from two years of field-based positioning experiments with detailed N balance assessments to elucidate the key mechanisms through which CRU mitigates N loss and optimizes N supply. The research thus aims to provide a scientific foundation for reducing synthetic fertilizer inputs while improving NUE in this critical agricultural region.

Therefore, the objective of this study is to clarify the N flux of CRU within each N input and output component of the maize-soil system using N balance calculation indicators, and to investigate the effects of single CRU application on N dynamics in the N balance system. Based on this framework, a two-year field experiment was conducted in Handan, Hebei Province. And our current hypothesis is as follows: (1) The single application of CRU can increase maize yield and enhance N uptake compared with the same application of urea in NCP of China; (2) The single application of CRU can effectively prevent N loss and contribute to emission reduction; (3) The single application of CRU can effectively both environmental sustainability and agricultural economic performance. Through the analysis of the experimental results, the N balance dynamics involving CRU were clarified, and it was assessed whether CRU application could serve as an improved N management strategy for farmland to address existing challenges in N management.

2 Materials and Methods

2.1 Site description

This experiment was conducted at the Qu Zhou Experimental Station of China Agricultural University in Qu Zhou County, Handan City, Hebei Province (36°87′N,115°02′E) in October 2020. The climate in Qu Zhou is warm-temperate sub-humid continental monsoon, with cold winters and hot summers, the planting system is winter wheat-summer maize rotation, and the soil type is brown soil developed from fluvo-aquic soil. The climate data of daily mean temperature and precipitation during the summer maize growth period from 2020 to 2021 are shown in Fig. 1 (climate data obtained from the website of "La Spezanepogold" LLC. https://rp5.ru ）. The daily mean temperatures are 24.6 ℃ and 24.4 ℃, respectively; The annual cumulative rainfall is 1983.3mm and 2607.3mm respectively.

2.2 Experimental Design

2.2.1 Regional Experimental Design

The experimental design adopted in this study followed a randomized block design, with each plot measuring 4 m × 7 m (length × width). To minimize edge effects, isolation zones were established between plots, and protective rows were planted around the perimeter of the experimental area. The experiment consisted of three treatments: CK (no N application), U (application of conventional urea at a N rate of 180 kg/hm²), and CRU (application of CRU at the same N rate as the U treatment). Each treatment was replicated four times. Phosphorus and potassium fertilizers were applied uniformly across all treatments at rates of 60 kg/hm² P_2O_5 and 60 kg/hm² K_2O, respectively. Conventional urea was applied in two splits, with a basal-to-topdressing ratio of 4:6; the topdressing was applied during the maize big horn stage (V12). CRUs were applied solely as basal fertilizers in a single application.

The fertilizers used in the experiment included the following: ordinary urea (46% N, supplied by Inner Mongolia Boda Field Chemical Co., Ltd.), CRU (polyurethane-coated urea with a 3-month release duration and 44% N content, developed by the Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences), calcium superphosphate (12% P_2O_5, supplied by Hubei Xing Fa Chemical Group Co., Ltd.), and potassium sulfate (52% K_2O, supplied by Guo Tou Xinjiang Lop Nur Potassium Salt Co., Ltd.). The maize cultivar used was 'Deng Hai 685'. In 2020, sowing was conducted on June 16, fertilization on July 28, and harvest on October 2. In 2021, sowing was carried out on June 10, fertilization on July 20, and harvest on October 10. Basal fertilizers were broadcast and incorporated into the soil using a rotary tiller. Topdressing was applied manually between maize rows. Irrigation was conducted manually after fertilization unless sufficient natural rainfall occurred. Maize was planted with a row spacing of 60 cm and a plant spacing of 22 cm, representing a high-density planting condition. All other field management practices-including thinning, irrigation, disease control, and weed management-were uniformly implemented across all treatments.

Prior to the establishment of the experiment, soil samples were collected from the 0–20 cm topsoil layer to determine its physicochemical properties, and the results are presented in Table 1.

2.2.2 Micro-zone Experimental Design

The specific micro-zone experimental design was structured as follows in 2020 and 2021: The experiment employed a randomized block design, consisting of three treatments-CK (no N application), U (ordinary urea treatment), and CRU (Equal nitrogen content to U)-with three replicates per treatment. A total of 36 square experimental plots, each with a side length of 60 cm, were established at regular intervals, with a defined spacing between each independent unit. Maize was cultivated under standard conditions within each micro-zone, without physical barriers separating the plots. Field management practices were maintained consistently with those applied in the surrounding field area.

The fertilization protocol was implemented as follows: Fertilization was carried out at the

center point of each square micro-zone, where N fertilizer was applied in a concentrated manner at a depth of 15 cm. The specific application rates were: CK, no N fertilizer; U, 16 g of ordinary urea; and CRU, 16 g of polyurethane-coated urea. Phosphorus and potassium fertilizers were uniformly applied across all treatments, with calcium superphosphate (20 g) and potassium sulfate (5 g) added to each micro-zone. All fertilizers were evenly distributed within the designated micro-zones.

For soil sampling, each micro-zone was divided into three concentric layers with radii of 10 cm, 20 cm, and 30 cm, respectively. Each layer contained 4 sampling points, resulting in a total of 12 sampling points per micro-zone. Soil samples were collected at 4 time intervals: 7, 14, 30, and 122 days after fertilization (post-harvest). Fresh soil samples were used to determine N_{min} content. All other agricultural management practices followed the same procedures as those in the previous experiment.

2.3 Sampling and Measurement

2.3.1 Nutrient Release Measurement of CRU

The nutrient release characteristics of CRU were evaluated from both still water and soil perspectives. The water immersion method is used to determine the urea release rate of polyurethane coating in still water. The main procedural steps are as follows: (1) preparation of reagents; (2) construction of standard curves; (3) determination of the fertilizer release rate through water soaking at 25 °C. These detailed procedures were conducted in accordance with GB/T 23348-2009. The formula for calculating the N release rate of fertilizers is as follows (Eq. 1; Eq. 2; Eq. 3; Eq.4):

$$\eta_{\Delta t} = (\eta_{tn} - \eta_{t1})/(t_n - t_1) \times 100\% \quad (1)$$

$$\eta_{t1} = M_{t1}/M \times 100\% \quad (2)$$

$$\eta = \sum n_{tn}/M \times 100\% \quad (3)$$

$$T = 1 + (80\% - \eta_{t1})/\eta_{\Delta t} \quad (4)$$

Among them, $\eta_{\Delta t}$ is the differential dissolution rate; η_{t1} is the initial dissolution rate; η is the cumulative release rate; T is the N release period. T_n is the nth day, t_1 is the 1st day, n_{tn} is the cumulative release rate on the nth day, η_{t1} is the initial dissolution rate, M_{t1} is the nutrient content dissolved on the 1st day, and M is the total nutrient content in the coated fertilizer.

The N release rate under field conditions was determined by using the embedding method (Zhang et al., 2015; Huang et al., 2019). Several nylon mesh bags, each measuring 10 cm in length and 8 cm in width, with a pore diameter of 1 mm, were prepared in advance. Each bag was filled with 10 g of polyurethane-coated urea particles and subsequently sealed. Pits approximately 15 cm deep were excavated at regular intervals across the field, with adequate spacing between them. The pre-weighed fertilizer was uniformly distributed within each nylon mesh bag and placed on the same horizontal plane. A total of 48 nylon mesh bags were buried, with identification labels positioned adjacent to each bag. This procedure was conducted simultaneously with the

application of the basal fertilizer in the experiment. Soil sampling was conducted on the 3rd, 7th, 14th, 28th, 42nd, 56th, 70th, and 84th days after burial, as well as on the 111th day following maize harvest. During each sampling event, three nylon mesh bags were randomly collected. The samples were transported to the laboratory, where the soil and residues adhering to the exterior surfaces of the mesh bags were meticulously removed using a soft brush and distilled water. Subsequently, the fertilizer particles inside the mesh bags were carefully extracted, wrapped in kraft paper, and dried in an oven at 60 °C until a constant weight was achieved. The samples were then weighed, and the nutrient release rate of the fertilizer was calculated accordingly (Eq. 5).

$$\alpha = （M_1 - M_2）/（M_1 - M_{film}）\times 100\% \quad (5)$$

In equation (5): α (%) is the nutrient release rate of fertilizer; M1 (g) is the mass of fertilizer particles before burial; M2 (g) is the dried weight of fertilizer particles after burial; M film (g) is the mass of the film in the fertilizer before burial. The coating rate of polyurethane coated urea used in this study is 4%.

2.3.2 Soil Sample Collection and Measurement

Soil samples were collected at different growth stages of maize in 2020 and 2021. The corresponding sampling dates and the number of days after sowing for each growth stage are summarized in Table 2. The sampling methodology involved the use of a soil auger to collect samples to a depth of 100 cm, with stratified sampling conducted at 20-cm depth intervals. Within each plot, three subsamples were collected and combined separately for each soil layer. The fresh soil samples were used for the determination of N_{min} content. The samples were processed through sieving, extraction, shaking, and filtration. The concentrations of ammonium N (NH_4^+-N) and nitrate N (NO_3^--N) were analyzed using a Bran+Luebbe 3-AA3 Auto-Analyzer (continuous flow analysis system, manufactured in Germany). The N_{min} concentration was calculated as the sum of NH_4^+-N and NO_3^--N concentrations. The soil organic matter, total N, available phosphorus, available potassium, pH and Ec are all determined according to the Soil Agro-chemical Analysis (Bao, 2001).

2.3.3 Plant Sample Collection and Measurement

Plant samples were collected during critical growth stages of maize, including the jointing stage, bell mouth stage, silk emergence stage, milk ripening stage, and maturity stage, across the growing seasons of 2020 and 2021. The specific growth stages, corresponding sampling dates, and days after sowing are summarized in Table 2.

The sampling and measurement procedure consisted of selecting three representative plants from each plot, collecting only the aboveground portions, and measuring their total fresh weight. Each plant was then divided into four components: stem, leaf, grain, and ear, which were weighed separately. The samples were initially killed at 105 °C for 30 minutes and subsequently dried to a constant weight at 75 °C, after which the dry weight of each plant component was recorded. The dried samples were then ground and sieved, and the N content of each plant part was analyzed using the Kjeldahl method (Bao, 2001). Based on the N content of individual plant components, the total aboveground N content was calculated.

2.3.4 Determination of maize yield and elements of productivity

Maize was harvested on October 4th, 2020, and October 10th, 2021, during the maturity stage, followed by grain yield measurement. The specific procedures were as follows: During harvesting, two representative rows were selected from each plot, with each row measuring 5 meters in length, resulting in a total measured plot area of $6m^2$. At late maturity, 40 ears were randomly selected from the central two rows of each plot for sampling. These ears were placed in gauze bags and air-dried under natural conditions. The number of ears, plants, and barren stems was recorded. Plant samples were subsequently air-dried indoors to constant moisture before threshing. Seed yield was calculated as the ratio of total grain weight to total ear weight. The oven-drying method was employed to determine moisture content and thousand-grain weight, and the measured yield was adjusted to a standard moisture content of 14%. The formula for calculating the actual yield is as follows (Eq. 6):

$$\text{Actual yield（kg/ha）} = \text{Grain weight of the tested maize(kg)}/\text{Test area}(m^2) \times \text{Germination rate} \times (1 - \text{Seed moisture content}(\%))/0.86 \times 10^4 \quad (6)$$

2.3.5 Calculation of N utilization efficiency

The calculation formulas for N fertilizer utilization efficiency, N fertilizer agronomic efficiency, and N fertilizer partial productivity are as follows (Eq. 7; Eq. 8; Eq. 9):

$$\mathrm{NUE} = (\mathrm{N_f} - \mathrm{N_{CK}})/\mathrm{Nr} \quad (7)$$

$$\mathrm{AUE} = (\mathrm{Y_f} - \mathrm{Y_{CK}})/\mathrm{Nr} \quad (8)$$

$$\mathrm{PNPF} = \mathrm{Y_f}/\mathrm{Nr} \quad (9)$$

In equation (7)、(8)、(9):NUE (%) refers to N fertilizer utilization efficiency; Nf (kg/hm^2) refers to the amount of N absorbed by the aboveground parts under N fertilizer treatment; NCK (kg/hm^2) refers to the amount of N absorbed by aboveground parts without N application treatment; Nr (kg) refers to the amount of N applied; AUE (kg/kg) refers to the agronomic efficiency of N fertilizer; Yf (kg/hm^2) refers to the yield of N fertilizer treatment; YCK (kg/hm^2) refers to the yield without N fertilizer treatment; PNPF (kg/kg) refers to the partial productivity of N fertilizer.

2.4 Emission of N gas Collection and Measurement

2.4.1 Collection and determination of soil ammonia volatilization (AV)

The determination of soil AV in this study mainly follows the methods of Li et al. (2015) and Gericke et al. (2011). The Delger ammonia tube method (DTM method) was employed to measure ammonia (NH_3) volatilization (Eq. 10; Eq. 11; Eq. 12), and the temporal dynamics of AV in the field were monitored over a 10-day period following both basal fertilization and topdressing.

When the ammonia concentration is relatively high, samples should be collected 2-3 times per day (at 6:00, 10:00, and 18:00); when the ammonia concentration is relatively low, samples should be collected only once per day (at 10:00); and if there are special weather conditions such as rainfall, the sampling time can be adjusted accordingly. Generally,

continuous sampling for 14 days should be conducted until the instrument no longer detects significant AV loss. This research experiment measured the changes in AV in the field before and after the application of base fertilizer, as well as within 10 days after the application. After 10 days, there was no significant loss of AV. The in-situ measurement formula of AV using DTM:

$$F_{Ng} = V \times |\ conc.\ | \times 10^{-6} \times \rho NH_3 \times U_N \times U_F \times U_Z \quad (10)$$

In equation (10):: F_{Ng}［N mg/（m^2·h）］represents the ammonia emission volume;; V（L）is the volume of the extracted gas;; | conc.|（μl/L）is the concentration of ammonia gas is the concentration of ammonia gas; ρNH_3（mg/L）is the density of NH_3 at the given temperature and pressure; $U_N$is the conversion factor for converting NH_3 to N based on molecular weight; U_F（m^2）is the surface area conversion factor is the surface area conversion factor; $U_Z$is the time conversion factoris the time conversion factor. The calculated AV amount needs to be corrected using meteorological methods (in two situations: winter and summer):

$$\text{Winter}\ \ln(NH_3\ flux_{IHF}) = 0.444 \times \ln(NH_3 flux_{DTM}) + 0.590 \times \ln(V_{2m}) \quad (11)$$

$$\text{Summer}\ \ln(NH_3\ flux_{IHF}) = 0.456 \times \ln(NH_3 flux_{DTM}) + 0.745 \times \ln(V_{2m}) - 0.280 \times \ln(V_{0.2m}) \quad (12)$$

In equation (11)、（12）:: $NH_3 flux_{IHF}$［N kg/(hm^2 h)］represents the AV amount determined by the IHF micro-meteorological method; V_{2m}（m/s）与 $V_{0.2m}$（m/s）respectively represent the wind speed at 2 m and 0.2 m from the ground; $NH_3 flux_{DTM}$［kg N/（hm^2 h）］represents the AV amount determined by the DTM method.

2.4.2 Collection and determination of N_2O in soil

The method for determining soil N_2O emissions in this study was based on previously established methodologies reported before (Ding et al., 2007; Xie et al., 2016; Xu et al., 2016; Hao et al., 2017). This experiment conducted continuous sampling during the first 10 days after fertilization, and then carried out interval sampling based on the sampling concentrations. During this period, the influence of rainfall was also taken into account. Uninterrupted sampling was carried out throughout the entire maize growth period (jointing stage、V12 stage、tasseling stage、blister stage、maturity). In detail, the sampling time is from 9:00a.m. to 10:00a.m. Gas samples are collected using a syringe and injected into 12 mL vacuum glass bottles in the field. Sampling is conducted every 10 minutes for a total of 5 times. The sampling time and the temperature inside the sampling box are also recorded. The collected gas samples are brought back to the laboratory and analyzed immediately using the GAS-256A gas chromatograph. The specific calculation formula is as follows (Eq. 13; Eq. 14; Eq. 15)：

$$F = \rho \times V/S \times dC/dt \times 273/(273 + T) \times 10^3 \quad (13)$$

$$A\ (kg\ ha^{-1}) = \sum\ (F_{i+1} + F_i)\ /2 \times (t_{i+1} - t_i) \times 24 \quad (14)$$

$$f = (A_F - A_{CK})/Nr \quad (15)$$

In equation (13)、(14)、(15): F(μg/(m^2·h)): Emission flux; ρ: The density of N_2O under standard conditions is 1.25 g/L; V（m^3）: Volume of the sampling box; S（m^2）: Surface area of the soil covered by the sampling box; dC/dt（μL/（L·h））: Rate of change of N_2O gas concentration in the sampling box; T（℃）: Average temperature in the static box Average temperature in the static box; A（kg/hm^2）: Cumulative emission flux of N_2O; i: The i-th

sampling；t：Sampling date Sampling date。f：Emission coefficient；A_F（kg/hm²）：Cumulative emission amount of N_2O in the N fertilizer application treatment；A_{CK}（kg/hm²）：Cumulative N_2O emission amount in the no-N application treatment；Nr（kg）：N application amount N application amount.

2.4.3 The Calculation of N balance

During the second quarter of maize planting, the fluxes of various N inputs and outputs were calculated. Detailed calculations of soil-plant N balance were conducted for the three treatments (CK, U and CRU) of summer maize in Quzhou, Hebei Province. All data were obtained through two methods: self-measurement and literature review. Among these, the N_{input} components include N derived from chemical fertilizers, straw return to the soil, non-symbiotic N fixation, dry and wet atmospheric deposition, irrigation water, and N contained in seeds. The N_{output} components include plant N_{uptake}, AV, N_2O emissions and nitrate leaching. The data sources for the quantification of N inputs and outputs are presented in Table 3. The N contributions from straw return and seed-borne N were obtained through independent measurements, and the corresponding calculation formulas are as follows (Eq. 16; Eq. 17):

$$N_{st} = M_{st} \times W_{st}/100 \quad (16)$$

In equation (16)：N_{st}(kg/hm²)indicates N from straw return；M_{st}(kg)represents the dry weight of straw returned per hectare for wheat；W_{st}(%) represents the percentage N content in the wheat straw. Note: The stems of the harvested wheat plants that have removed the grains are approximately regarded as the part for returning to the soil as crop residue. The dry weight of wheat straw returned to the soil is the percentage of nitrogen content in the wheat straw.

$$N_{se} \equiv M_{se} \times W_{se}/100 \quad (17)$$

In equation (17)：N_{se}: (kg/hm²) Nitrogen content in the seed; M_{se}: (kg) Seed sowing rate per hectare; W_{se}: (%)Nitrogen content percentage in the seeds. The sowing rate of maize per hectare is 37.5 kg, and the nitrogen content percentage in the seeds is 1.4%.

Regarding N balance (the calculation method is as follows (Eq. 18))：

$$N_b = N_{ins} - N_{outs} \quad (18)$$

In equation (18)：N_b（kg/hm²）：N balance；N_{ins}（kg/hm²）：total N_{input}； N_{outs}（kg/hm²）：total N_{output}.

2.5 Statistical Analysis

Data management and statistical analysis, including analysis of variance (ANOVA), were performed using Microsoft Excel 2019 and SPSS 26. Graphs were generated using Origin 2021 (Origin Lab, USA). Mean comparisons were conducted using the least significant difference (LSD) test.

3. Results

3.1 N release characteristics of CRU

As illustrated in Fig. 2, the graphs depict the nutrient release profiles of CRU under static water conditions at 25 °C and under field conditions. The release period of CRU is defined as the time required to achieve an 80% cumulative N release (Yang et al., 2013). Under static water conditions, the release pattern of CRU follows an S-shaped curve, with a release duration of

approximately 3 months. During the initial 24 hours, the release rate was very slow, with a cumulative N release of only 0.4%, and a cumulative release of 31.7% within 28 days. This indicates that the polyurethane coating used in this experiment was relatively intact, and its release behavior met the performance standards for CRU (HG/T 5517-2019). From the 14th to the 43thday after immersion, the N release rate increased significantly, reaching a cumulative release of 51.5% by the 43th day. By the 71st day, the cumulative release rate under static water conditions reached 71.2%.

Notable differences were observed in the release behavior of CRU under field conditions compared to static water conditions at 25 °C. In soil, the release pattern of CRU exhibited a more linear trend. The release period in soil was shorter, lasting approximately 70 days, with a cumulative N release of 39.0% within 28 days. Overall, the release rates across different time intervals were relatively balanced. However, the release rates between the 14th and 28th days were slightly higher, with a cumulative N release of 22.4%.

3.2 Effects of different fertilization treatments on summer maize yield，N_{uptake} regulations and NUE

As shown in Fig. 3, The effects of different years, fertilization treatments, and their interactions on the yield of summer maize were significant ($P < 0.001$). In 2020, due to the relatively high soil base fertility, there was no significant difference in yield between CK and the applied-N treatment (U, CRU); in 2021, the yield of the applied-N treatment significantly increased, with the CRU treatment increasing by 9.6% compared to the U treatment and by 69.4% compared to CK. The average results of the two years showed that CRU treatment significantly increased the yield by 8.0% compared to U ($P < 0.01$), indicating that CRU has a stable promoting effect on yield.

As illustrated in Fig. 4, significant differences in N_{uptake} by maize plants were observed between the two years ($P < 0.05$). In 2021, the N_{uptake} levels at the harvest stage for the CK, U, and CRU treatments were 58.7%, 34.9%, and 33.3% higher, respectively, than those in 2020. The N_{uptake} patterns across both years followed a similar "S"-shaped curve: N_{uptake} progressed slowly from sowing to the jointing stage, accelerated during the mid-growth stages (from the large ear stage to the milk and dough stages), and stabilized in the later growth stages. Moreover, the CRU treatment significantly improved both the agronomic efficiency of nitrogen fertilizer (NAE) and the partial productivity of nitrogen fertilizer (PNPF) by 34.2% and 8.0%, respectively, compared to the U treatment ($P < 0.05$). In 2021, the NAE value for the CRU treatment reached 24.0 kg/kg, which was significantly higher than the 17.9 kg/kg recorded for the U treatment. These findings further confirm the effectiveness of CRU in synchronizing nitrogen supply with crop demand, particularly in the second year following soil N depletion, where the benefits were more evident.

In 2020, soil fertility was high, and there was no significant difference in aboveground N_{uptake} between CK and other fertilized treatments. When calculating NUE using the difference method, the efficiency levels were relatively low across all N fertilizer treatments, ranging from 6.9% to

18.1% (Table 4). The NUE of the U treatment was significantly lower than that of the CRU treatment by 11.3%. No significant differences were observed in NAE or N partial productivity among the different N fertilizer treatments. In 2021, the total aboveground N_{uptake} under the CK treatment was significantly lower than that under the U and CRU treatments by 39.0% and 44.5%, respectively. Meanwhile, the application of CRU increased NUE by 9.2%. The agronomic efficiency and partial productivity of N in the U treatment were 25.4% and 8.8% lower, respectively, than those in the CRU treatment. Averaged over the two years, compared to U, the application of CRU significantly increased the agronomic efficiency of N and the N productivity bias by 34.2% and 8.0%, respectively.

3.3 Dynamic changes of soil N_{min} during different maize growth stages

As illustrated in Fig. 5, the soil N_{min} content exhibited dynamic variations throughout the maize growth period, with its distribution pattern closely influenced by the fertilization method. Prior to sowing, the N_{min} content in the 0–20 cm soil layer across all treatments was relatively low, ranging from 12.5 to 16.3 mg/kg, and it generally decreased with increasing soil depth. Following basal fertilizer application, the N_{min} content in the N-applied treatments (U and CRU) at the jointing stage was significantly higher than that in the CK treatment. Specifically, the U treatment showed a decreasing trend with soil depth, whereas the CRU treatment exhibited an approximately 20% higher N_{min} content in the 0–40 cm plow layer compared to the U treatment. During the large-flower stage, as plant N uptake intensified, the overall N_{min} content across all treatments declined. Notably, the N_{min} content in the 60–80 cm soil layer under the U treatment (20 mg/kg) was significantly higher than that under the CRU treatment, indicating more pronounced N leaching in the U treatment.

During the maize harvest period, the soil N_{min} content in the 0–20 cm and 20–40 cm soil layers under the CRU treatment was significantly higher than that under the U treatment, with increases of 65.9% and 71.0%, respectively. In contrast, the N_{min} content in the 60–100 cm soil layer of the U treatment ranged from 10.3 to 10.6 mg/kg, which was significantly greater. These findings indicate that CRU can enhance N availability in the topsoil, reduce nitrate leaching to deeper soil layers, and maintain the soil's N supply capacity during critical maize growth stages.

With regard to the impact of applying CRU on the spatio-temporal distribution of soil N_{min}, the study was conducted at two scales: micro-scale spatial distribution and crop growth period. As illustrated in Fig. 6, at the micro-scale, 7–14 days after fertilization, the U treatment exhibited significant spatial heterogeneity: in the 0–20 cm soil layer, the N_{min} content at a distance of 10 cm from the fertilization point ranged from 90.3 to 133.4 mg/kg, which was 4.6 to 6.5 times higher than that at 20-40 cm depth, with a coefficient of variation (CV) as high as 65%–82%. In contrast, the CRU treatment showed a more uniform distribution across the entire soil profile, with N_{min} contents ranging from 12.8 to 20.1 mg/kg and a CV of only 18%–25%. These findings indicate that the sustained-release properties of the polyurethane coating effectively mitigated N-induced disturbance in the soil. Meanwhile, the U treatment showed a significant enrichment of inorganic

nitrogen in the 10 cm circle of the 0 – 20 cm soil layer (7d), with a concentration of 90.3 mg/kg, which was approximately 365% higher than that of the CRU treatment (19.4 mg/kg), By day 14, the concentration at this point in the U treatment further increased to 133.4 mg/kg, which was approximately 468% higher than that of the CRU treatment (23.5 mg/kg). This is equivalent to the CRU's handling reducing the initial local inorganic nitrogen disturbance caused by urea during fertilization by 78% to 82%, indicating that the rapid hydrolysis of urea led to local nitrogen accumulation, intensifying the risk of leaching and volatilization. In contrast, the CRU treatment had a uniform distribution across all soil layers during the same period, with coefficient of variation less than 15% at both 7d and 14d, reflecting that controlled-release urea effectively and steadily released nitrogen through its slow-release mechanism, reducing environmental disturbance.

At the reproductive growth stage (30 days after fertilization), the N_{min} content in the 40–60 cm soil layer under the U treatment increased due to leaching, whereas the corresponding value for the CRU treatment was only 59% of that observed under the U treatment. Following maize harvest (122d), the N_{min} content in the 0–40 cm soil layer under the CRU treatment was 65.9–71.0% higher than that of the U treatment, while in the 60–100 cm soil layer, it was 38.2–41.6% lower. The concentration gradient index (CGI) and vertical migration coefficient (VMC) values for the U treatment were 70.7–112.8 mg/kg and 0.31–0.49, respectively, which were significantly higher than those for the CRU treatment (3.2–5.8 mg/kg and 0.68–0.81). These findings indicate that CRU can reduce the intensity of soil N disturbance by 78–93%, thereby effectively mitigating the "burst release–rapid migration" phenomenon associated with conventional urea application.

3.4 Effects of different fertilization treatments on N loss

Overall, the AV rate across all treatments followed a pattern of initial increase followed by a gradual decline after fertilization. Within the first five days post-fertilization, the U treatment consistently exhibited high AV and release rates, ranging from 0.9 to 2.4 kg/hm²/d, as illustrated in Fig. 7. The first emission peak occurred on the first day after fertilization, reaching 1.6 kg/hm²/d. Influenced by rainfall events, AV0 increased significantly on the fourth day, with the emission rate peaking at 2.4 kg/hm²/d on the fifth day. As the sampling period progressed, the volatilization rate gradually declined, and by the ninth and tenth days after fertilization, ammonia emissions were nearly undetectable. In contrast, the CRU treatment exhibited a much smaller fluctuation range, with a maximum emission peak of 1.1 kg/hm²/d, significantly lower than that of the U treatment. The U treatment showed high AV rates between two and three days after fertilization, with a peak of 2.6 kg/hm²/d. By the fifth day, the emission rate had decreased to 1.2 kg/hm²/d and continued to decline gradually thereafter, as shown in Fig. 7. The AV pattern under the CRU treatment was relatively stable, with only minor emissions observed on certain days.

The cumulative AV emissions across all three treatments exhibited a steady upward trajectory throughout the observation period, reflecting a dynamic and evolving process. In the case of the U treatment, the vast majority of AV occurred within the initial seven days following fertilization.

More precisely, an impressive 93.3% of total AV was released within the first week after basal fertilization, while 77.0% occurred during the same period following topdressing. Following basal fertilization, the cumulative AV under the U treatment soared to 9.2 kg/hm²—an emission level that dwarfed the corresponding values for both the CK treatment (1.0 kg/hm²) and the CRU treatment (4.4 kg/hm²). Similarly, after topdressing, the U treatment registered a striking AV emission of 7.7 kg/hm², markedly surpassing those of the CRU treatment (3.2 kg/hm²) and the CK treatment (1.8 kg/hm²). These compelling findings underscore the remarkable efficacy of CRU in curbing AV, achieving reductions of 57.4% after basal fertilization and 54.4% after topdressing when compared to conventional urea.

As depicted in Fig. 8, the U treatment was characterized by a striking and abrupt emission peak following fertilization, whereas the CRU treatment demonstrated a remarkably stable and subdued emission pattern, with only minor fluctuations throughout the observation period. The application of U triggered intense N_2O emissions, peaking on the 4th day after basal fertilization and the 7th day after topdressing, reaching impressive levels of 487.7 μg/m²/h and 497.1 μg/m²/h, respectively. Furthermore, N_2O emissions remained consistently elevated for up to two weeks following urea application, signaling a prolonged environmental impact. In stark contrast, the CRU treatment, benefiting from the controlled-release properties of its membrane shell, exhibited a significantly diminished emission peak—substantially lower than that of the U treatment—despite a modest increase during the maize growth phase. The highest N_2O emission under the CRU treatment was recorded at 176.5 μg/m²/h on the 13th day after basal fertilization, a figure that pales in comparison to the towering peak observed in the U treatment. Across the entire maize growth cycle, cumulative N_2O emissions from the CK, U, and CRU treatments amounted to 0.5 kg/hm², 2.6 kg/hm², and 0.8 kg/hm², respectively, translating into emission factors of 1.2% for the U treatment and a mere 0.2% for the CRU treatment. These compelling results reveal that the application of CRU, at the same N input level, can dramatically reduce cumulative N_2O emissions by 68.8% compared to conventional urea, underscoring its profound potential in mitigating greenhouse gas emissions from agricultural systems.

3.5 Correlation Analysis Reveals Key N Loss Pathways Limiting Maize Yield

To reveal the intrinsic relationships between summer maize yield, core soil physicochemical properties and dominant nitrogen (N) loss pathways under conventional urea (U) and controlled-release urea (CRU) treatments, Pearson correlation analysis was conducted on yield, ammonia volatilization (AV), N_2O emissions, nitrate nitrogen leaching and key soil mineral N indicators (Fig. 9). The results indicated that the yield was significantly negatively correlated with N_2O emissions ($r = -0.69$, $P < 0.01$) and nitrate nitrogen leaching ($r = -0.64$, $P < 0.01$), but not significantly correlated with ammonia volatilization ($r = -0.27$, $P > 0.05$), suggesting that under the conditions of this experiment, N_2O emissions and nitrogen leaching losses are the key environmental limiting factors affecting maize yield. In addition, ammonia volatilization was extremely significantly positively correlated with N_2O emissions ($r = 0.86$, $P < 0.01$), and also

significantly positively correlated with leaching ($r = 0.69$, $P < 0.05$), indicating that the three occurred in a coordinated manner and might jointly respond to excessive nitrogen supply or improper management. This is quantitative evidence in the North China Plain summer maize system that N_2O emission and nitrate leaching rather than ammonia volatilization are the dominant environmental constraints to yield formation.

For soil physicochemical properties, Nmin content in the 0–40 cm root-zone soil was significantly positively correlated with maize yield ($r = 0.62$, $P < 0.05$) and significantly negatively correlated with AV, N_2O emissions and nitrate leaching ($r = -0.58$ to -0.65, $P < 0.05$). Soil organic matter, total N and available potassium also exhibited significant positive correlations with yield ($r = 0.51$–0.57, $P < 0.05$) and negative correlations with all N loss pathways, demonstrating that improved soil fertility enhances N supply stability and reduces N loss risk.

Under U treatment, rapid urea hydrolysis induced an abrupt increase in soil NH_4^+-N and NO_3^--N concentrations, which directly strengthened the synergistic occurrence of AV, nitrification–denitrification and nitrate leaching, resulting in massive reactive N loss and insufficient N supply for post-silking maize growth. In contrast, the controlled-release property of CRU maintained stable and moderate Nmin levels in the topsoil, reduced the N loss processes, and broke the synergistic enhancement among multiple N loss pathways, achieving a win-win situation of "environmental emission reduction" and "crop yield increase".

3.6 Effects of different fertilization treatments on N balance and economic benefits

In 2021, detailed N balance calculations were conducted for two N fertilizer treatments: U and CRU in the summer maize system in Quzhou, Hebei, as presented in Table 5. Regarding N_{input} components under the two fertilization treatments, the CRU treatment introduced 22.6% more N into the system through straw returning compared to the U treatment. However, the flux of other N_{input} components remained identical between the two treatments. N fertilizer, as the primary N source, accounted for 73.8% and 71.9% of total N_{input} under the U and CRU treatments, respectively. Secondly, N_{input} from straw returning to the field was also significant, contributing 11.6–13.9% of the total N_{input}. Additionally, N entering the soil-plant system from the external environment-including irrigation water, rainfall, and non-symbiotic N fixation-constituted another component of N_{input}.

The total loss of active N-including AV, N_2O emissions, and nitrate leaching-was 44.5 kg/hm² under CRU treatment and 68.5 kg/hm² under U treatment. Among these three N loss pathways, nitrate leaching resulted in the greatest N loss. Specific emissions of AV and N_2O were detailed in the previous section and will not be repeated here. Overall, plant N_{uptake} and N loss under CRU treatment accounted for 68.1% and 28.1% of total N_{output}, respectively, compared to 73.0% and 17.7% under U treatment. Compared with the U treatment, the CRU treatment increased plant N_{uptake} by 9.9%, reduced total active N loss by 35.5%, and decreased N surplus by 13.0%. Although the N balance values in Table 5 show minimal differences between the two fertilization

treatments, the application of CRU facilitates greater N transfer to the plant N pool and reduces soil N loss.

The economic benefits of different treatments were calculated in Table 6. The total cost comprises N fertilizer expenses and labor costs associated with fertilization. Excluding these two components, all other costs remain identical across treatments. In 2020, CK treatment achieved higher yields without incurring N fertilizer costs due to the high soil basic fertility, resulting in greater net income-5.1% higher than U treatment and only 4.7% lower than the CRU treatment. However, in 2021, CK treatment yielded significantly lower maize production due to the absence of N fertilizer application and the depletion of soil N reserves. Consequently, the net income from the CK treatment was 43.3% and 50.8% lower than that of the U and CRU treatments, respectively. Although CRU is 15.2% more expensive than U, its use reduces labor costs for topdressing and delivers higher yield benefits. As a result, the net income per hectare from maize production using CRU is 2,514.5 yuan higher than that from ordinary urea, equivalent to an increase of 167.6 yuan per mu. Averaged over the two years, the results indicate that the net income under CK treatment was 19.4% lower than that under the U treatment, whereas the net income under the CRU treatment was 12.7% higher than that under the U treatment.

4. Discussion

4.1 The effects of CRU on the increase of maize production and NUE

The results of this study show that, compared with the split application of ordinary urea (U), CRU with equivalent N content (CRU) significantly increased summer maize yield by 8.0% ($P < 0.01$). This finding is consistent with previous studies, which have reported yield increases ranging from 5% to 10% (Zhu et al., 2020; Zou et al., 2022). The observed yield improvement can be attributed to the synchronized release of N from CRU with crop demand, which enhances key grain-filling parameters, promotes the activity of key enzymes involved in N metabolism—such as nitrate reductase and glutamine synthetase—and facilitates the translocation of amino acid N to developing kernels during the grain-filling stage, thereby improving crop filling characteristics (Sun et al., 2024; Cao et al., 2021).

Concurrently, CRU extends the duration of photosynthetic function and increases dry matter accumulation, contributing to higher summer maize yields (Yu et al., 2023). The Nmin content in the 0–40 cm soil layer under CRU was 65.9–71.0% higher than that under U, further demonstrating CRU's ability to reduce N leaching and optimize N availability in the root zone (Zhou, 2023). Furthermore, the application of CRFs significantly increased the concentrations of soluble sugars, starch, protein, and fat in maize kernels. This stable nutrient supply minimizes physiological fluctuations that could disrupt crop metabolic processes, thereby enhancing maize grain quality (Yu, 2024). In summary, the effectiveness of CRU is attributable to its optimized nutrient release pattern, enhancement of key physiological processes, and capacity to improve both the productivity and quality of summer maize.

4.2 The inhibitory effect and mechanism of CRU on N loss

When N fertilizer is applied to the soil, it generally follows three primary pathways: uptake by maize, N loss, and residual retention in the soil (Zhu, 1998). CRU effectively mitigates N loss through a multi-dimensional synergistic mechanism. In calcareous soils of northern regions, the polymer coating reduces the direct contact between urea and urease, thereby significantly decreasing AV—by 57.4% after basal fertilization and 54.4% after topdressing application. This is consistent with previous findings, which demonstrate that CRU reduces AV concentration and ammonia partial pressure at the soil surface, thereby minimizing N losses (Zhou et al., 2016; Liu et al., 2019). CRU releases N via a membrane-controlled release mechanism, extending the N release duration to approximately 70 days and maintaining soil inorganic N at a moderate level of 20-30 mg/kg. This not only meets the peak N demand of maize during the jointing and tasseling stages but also avoids environmental risks associated with excessive N concentrations (Ju and Gu, 2014).

Furthermore, relevant studies have shown that the residual nitrate N from CRF application is primarily concentrated in the surface root distribution zone, effectively reducing its downward leaching into deeper soil layers (Shi et al., 2018; Sun et al., 2024). This aligns with the findings of the present experiment, in which the CRU treatment reduced nitrate N loss by 27.3% compared to U treatment, with retained N predominantly localized in the 0–40 cm vertical root zone. Notably, 7 to 14 days after fertilization, CRU significantly reduced the N concentration gradient in the 0–20 cm soil layer around the fertilization point, decreasing the coefficient of variation of Nmin content from 65–82% to 18–25%. This mitigation of excessive N concentration helps avoid salt stress and sharp fluctuations in soil pH, thereby maintaining the structural and functional stability of the soil microbial community and indirectly minimizing N losses (Ding et al., 2022). The ammonium ions released from CRU can stabilize rhizosphere pH within the optimal range of 6.0–7.5, promoting the availability of soil phosphorus and iron, while reducing soil electrical conductivity (EC) by 30–50% (Zhong and Dong, 2023). Additionally, CRU reduced N_2O emissions by 68.8%, as its controlled-release properties regulate the N release rate, maintaining low substrate availability (NH_4^+-N and NO_3^--N) for nitrifying and denitrifying bacteria. Consequently, this suppresses microbial production of N_2O and reduces overall soil emissions (Qiao et al., 2022; Xie et al., 2016).

The reduction of these N loss pathways significantly improves NUE and overall N balance. The N surplus under CRU treatment was 13.0% lower than that under the U treatment, approaching the recommended surplus level for sustainable maize production systems (Ju and Gu, 2017). By minimizing N leaching and gaseous emissions, CRU enhances internal N cycling efficiency and promotes greater N allocation to plant biomass (Zhu, 1998).

The significant negative correlations between yield and N_2O emissions, as well as nitrogen leaching ($r = -0.69, -0.64$) in this study indicate that reducing these two loss pathways has a direct positive effect on increasing corn yield. This is consistent with the research conclusion of Zhang et al. (2019) in the wheat-corn rotation system in the North China Plain, where nitrogen loss through

leaching and gaseous loss leads to insufficient effective nitrogen supply in the root zone, thereby affecting grain filling and biomass accumulation. It is notable that the correlation between ammonia volatilization and yield is weak (r = -0.27), possibly due to the fact that ammonia volatilization mainly occurs in the early stage of fertilization and has limited impact on nitrogen supply in the middle and late stages; while N_2O emissions and leaching occur throughout the growth period and continuously affect the soil nitrogen availability (Wang et al., 2024). Moreover, the strong positive correlation between ammonia volatilization and N_2O emissions (r = 0.86) suggests that optimizing fertilization techniques (such as deep application, controlled release) can simultaneously reduce multiple gaseous losses of nitrogen. The CRU significantly reduces N_2O and leaching losses through its slow-release characteristics, achieving a synergistic improvement in "increased yield and reduced emissions". This represents a key breakthrough compared with traditional fertilization, and explains why CRU achieved both higher yield and lower N footprint.

4.3 The effects of CRU on enhancing agronomic efficiency, environmental benefits, and economic benefits

In this study, CRU increased NAE and PNPF by 34.2% and 8.0% respectively, and significantly increased NUE by 10.6%. This indicates that applying CRU can synergistically enhance crop nutrient uptake, thereby promoting N assimilation (Zhang et al., 2019; Yao et al., 2021). Moreover, CRU demonstrates considerable potential in reducing environmental N loss. Compared with U, CRU can reduce AV by 55%, decrease cumulative N_2O emissions by 68.8%, decline nitrate leaching by 27.3%, and decrease apparent N loss by 35.5%. This is consistent with previous findings showing that CRFs can significantly reduce reactive N losses in dryland maize systems (Liang, 2024; Xie et al., 2016). Despite the higher initial cost of CRU fertilizer, the integration of labor savings from single basal application and increased yield led to a 12.7% higher net income per hectare compared to conventional split urea application. When external environmental costs—such as the contribution of NH_3 to $PM_{2.5}$ formation and the global warming potential of N_2O—are accounted for, research indicates that CRU can further increase comprehensive benefits by 6.4% (Yang et al., 2021). Yao et al. (2021) also reported that combining CRU with conventional urea proportionally improves environmental and economic performance.

In conclusion, CRU represents the preferred solution for intensive N management in croplands of the NCP, having achieved the integrated objective of "high yield with low carbon emissions" for summer maize.

5 Conclusion

This study evaluated the N management performance of CRU in a summer maize system within the North China Plain through two consecutive years of field experiments. The key findings are as follows: the application of CRU effectively optimizes N management by synchronizing N supply with crop demand, thereby achieving simultaneous improvements in grain yield, NUE, and environmental sustainability. Compared with conventional urea, CRU

significantly increased grain yield by 8.0%, while enhancing NUE and NAE by 10.6% and 34.2%, respectively. The temporal and spatial distribution of soil mineral N was substantially optimized, with greater retention observed in the 0–40 cm root zone, and nitrate leaching was reduced by 27.3%. Furthermore, CRU reduced N_2O emissions by 68.8%, decreased apparent N losses—including active N losses—by 35.5%, and increased farmers' net income by 12.7%, equivalent to an additional 2,514.5 yuan per hectare. Overall, the adoption of CRU represents a green and efficient fertilization strategy that promotes yield and income gains for summer maize cultivation in the North China Plain, reduces the N footprint, and supports the sustainable development of agricultural ecosystems.

CRediT authorship contribution statement

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Data availability

Data will be made available on request.

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Table 1 Soil basic physical and chemical properties in the experimental site

Organic matter (g/kg)	total N (g/kg)	total phosphorus (g/kg)	available phosphorus (mg/kg)	available potassium (mg/kg)	Nmin (mg/kg)	pH	Ec value (μs/cm)
17.2	0.9	0.5	12.7	109.7	35.7	8.0	233.3

Note: Soil basic physical and chemical properties in the experimental site in Quzhou ,Hebei.

Table 2 Reference table of sampling time during maize growing periods

Year	Maize growing periods	Date (Month/ Day）	Days after sowing (d)
2020	jointing stage	July 10th	24
	V12 stage	July 30th	44
	tasseling stage	August 14th	59
	blister stage	September 4th	80
	maturity	October 4th	110
2021	jointing stage	July 4th	24
	V12 stage	August 1st	52
	silking stage	August 18th	69
	milk stage	September 7th	89
	maturity	October 10th	122

Note:d:day. Sampling times for different growth stages of corn in 2020 and 2021.

Table 3 Data resources of soil N input and output items (0-100 cm)

N input and output items	Data resources
Fertilizer	Measurement
Straw return	Measurement
Seed	Measurement
Asymbiotic fixation N	(Zhu, 1992)
Precipitation	(Zhang et al., 2006)
Irrigation	(Liang, 2015)

N input and output items	Data resources
N_{uptake} of plant	Measurement
AV N losses	Measurement
N_2O emission losses	Measurement
N leaching	(Zhang et al., 2019; Zhao et al., 2009)

Note: Data resources of soil N input and output items

Table 4 Effects of different fertilization treatments on Nuptake and NUE of maize

Year	Treatment	TNK (kg/hm^2)	NUE (%)	NAE (kg/kg)	PNPF (kg/kg)
2020	CK	245.7±11.2b			
	U	255.0±6.8a	8.95±2.3b	4.11±0.8a	62.5±1.8a
	CRU	273.6±10.0a	20.89±4.2a	5.54±3.6a	66.5±2.4a
2021	CK	101.4±5.7b			
	U	166.1±4.8a	35.94±2.6b	17.9±2.6b	63.4±2.6b
	CRU	182.6±11.0a	45.12±8.9a	24.0±2.0a	69.5±1.4a
Average	CK	173.6±6.0b			
	U	210.5±3.1a	22.45±2.3a	11.0±1.0b	63.0±0.7b
	CRU	228.1±9.5a	33.01±6.4a	14.8±1.2a	68.0±1.1a
ANOVA					
Y		***	**	***	NS
T		*	*	NS	NS
Y*T		NS	***	NS	NS

Note:CK: No N fertilizer input ; U: Application of conventional urea; CRU: Application of controlled release urea. Different lowercase letters within a single column indicated significant differences between the treatments by the LSD test in the same year ($P \leq 0.05$). The significance of year (Y), treatment (T) and the interaction effects between them (Y×T) on the yield was shown. "NS", not significant; "*", significant at $=P<0.05$; "**", significant at $=P<0.01$ and "***", significant at $=P<0.001$.

Table 5 Soil N balance in summer maize season in Quzhou of Hebei province

N_{input} and N_{output} items	U (kg/hm^2)	CRU (kg/hm^2)

Input			
Fertilizer	180.0	180.0
Straw return	28.3	34.7
Seed	0.5	0.5
Asymbiotic fixation N	15.0	15.0
Precipitation	15.1	15.1
Irrigation	4.9	4.9
Output		
N_{uptake} of plant	166.1	182.6
AV_{losses}	16.9	7.6
N_2O emission N loss	2.6	0.8
Leaching	49.0	35.8
N surplus	77.7	67.6
N Balance	9.2	23.4

Note:U: Application of conventional urea; CRU: Application of controlled release urea.

Table 6 The costs and economic benefits of different fertilization treatments (Unit: CNY/hm^2)

Year	Treatment	The cost of N fertilizer	Fertilization labor cost	Other cost	Yield benefit	Net income
2020	CK		180.0	7559.0	28293.9	20554.9
	U	1291.0	630.0	7559.0	29040.4	19560.4
	CRU	1555.0	180.0	7559.0	30865.6	21571.6
2021	CK		180.0	7559.0	19056.4	11317.4
	U	1291.0	630.0	7559.0	29446.7	19966.7
	CRU	1555.0	180.0	7559.0	32278.6	22984.6
Average	CK		180.0	7559.0	23675.2	15936.2
	U	1291.0	630.0	7559.0	29243.6	19763.6
	CRU	1555.0	180.0	7559.0	31572.1	22278.1

Notes: The price of conventional urea and CRU was 3.3 CNY/kg, 3.8 CNY/kg respectively. The application rate of maize special fertilizer was 600 kg/hm^2, the price of maize special fertilizer was 3.125 CNY/kg. The labor costs of base fertilization and top-dressing fertilization for one-time were 180, 450 CNY/hm^2 respectively. The costs of P and K fertilizers were 680, 392 CNY/hm^2 respectively. Other costs included seeds, mechanics, herbicide, insecticide, irrigation, which were 1200, 1950, 1200, 162, 1975 CNY/hm^2 respectively. The price of maize kernels was 2.60 CNY/kg.

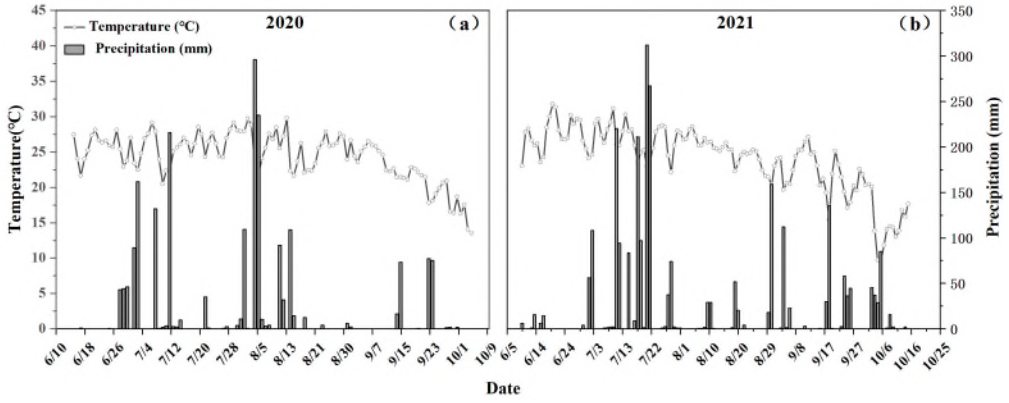


Fig. 1 Dynamics of daily mean temperature and precipitation of the experimental site for maize growing seasons in 2020-2021

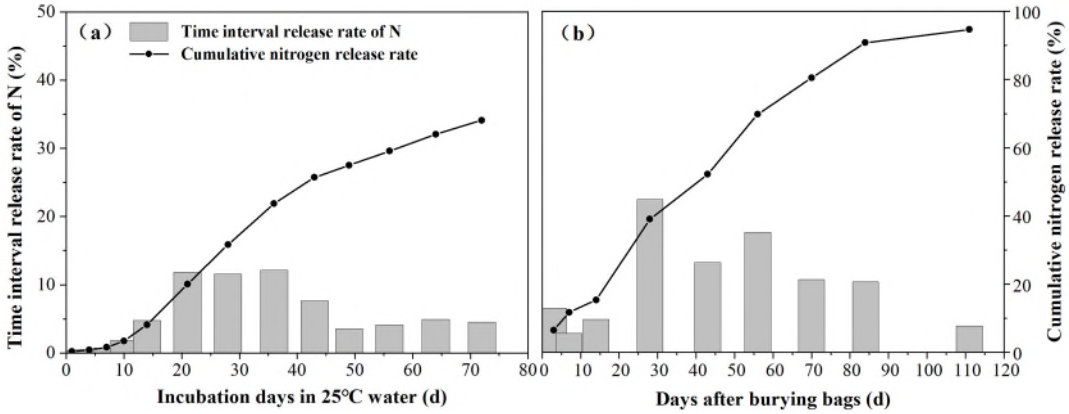


Fig. 2 N release rate of CRU in 25℃ water (a) and under field conditions (b)

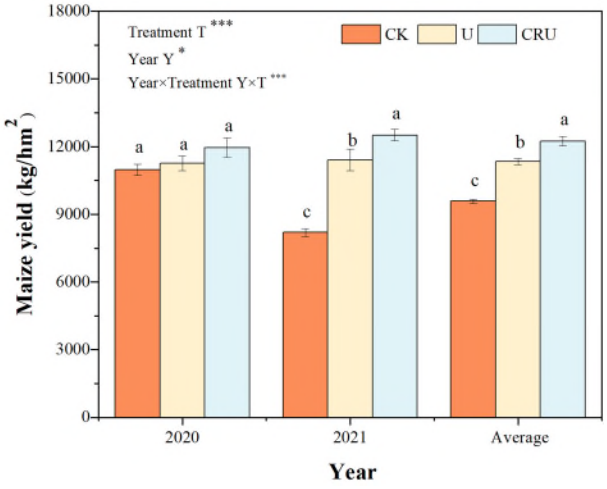


Fig. 3 The maize yields of different fertilization treatments in 2020-2021

Notes: CK: No N fertilizer input; U: Application of conventional urea; CRU: Application of controlled release urea. Different lowercase letters within a single column indicated significant differences between the treatments by the LSD test at the same year (P<0.05). The significance of year (Y), treatment (T) and the interaction effects between them (Y×T) on the yield was shown. "NS", not significant; "*", significant at =$P<0.05$; "**", significant at =$P<0.01$ and "***", significant at =$P<0.001$.

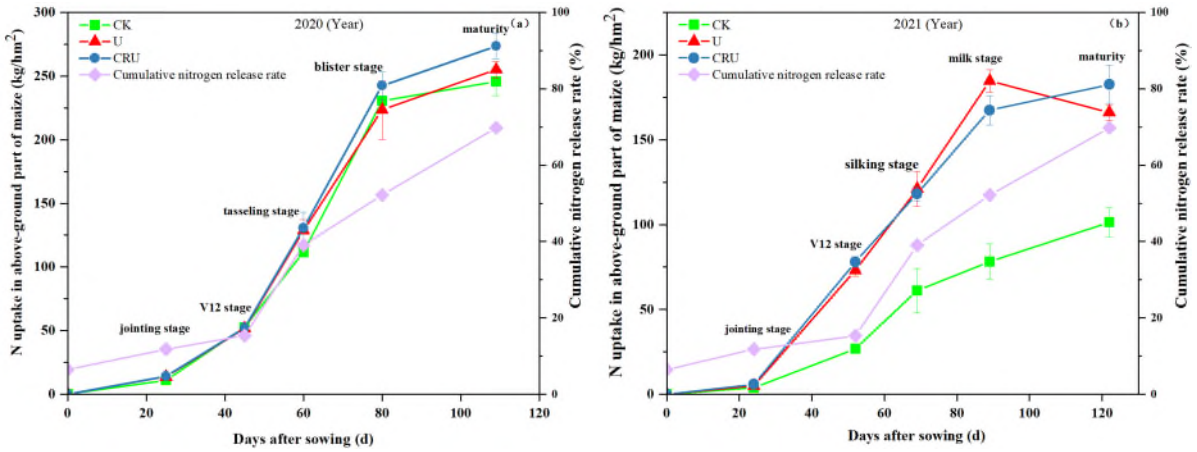


Fig. 4 The N_{uptake} of above-ground part during different maize growing periods in 2020 (a)、2021 (b) and N release rate of CRU

Notes: CK: No N fertilizer input; U: Application of conventional urea; CRU: Application of controlled release urea.

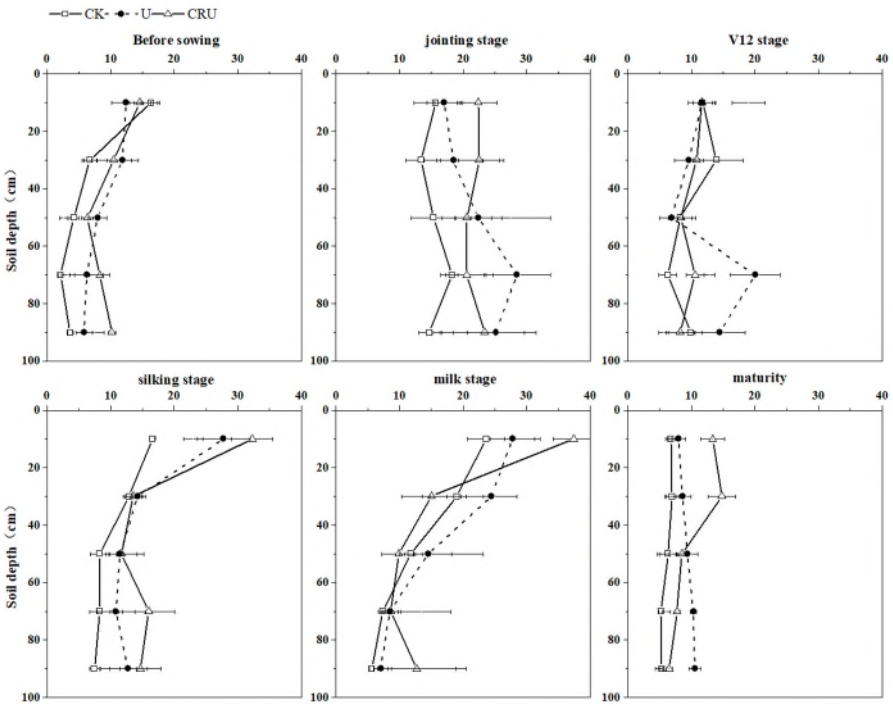


Fig. 5 The N_{min} dynamics in 0-100 cm soil layer of different maize growing periods Unit: mg/kg.

Notes: Unit: mg/kg. CK: No N fertilizer input; U: Application of conventional urea; CRU: Application of controlled release urea.

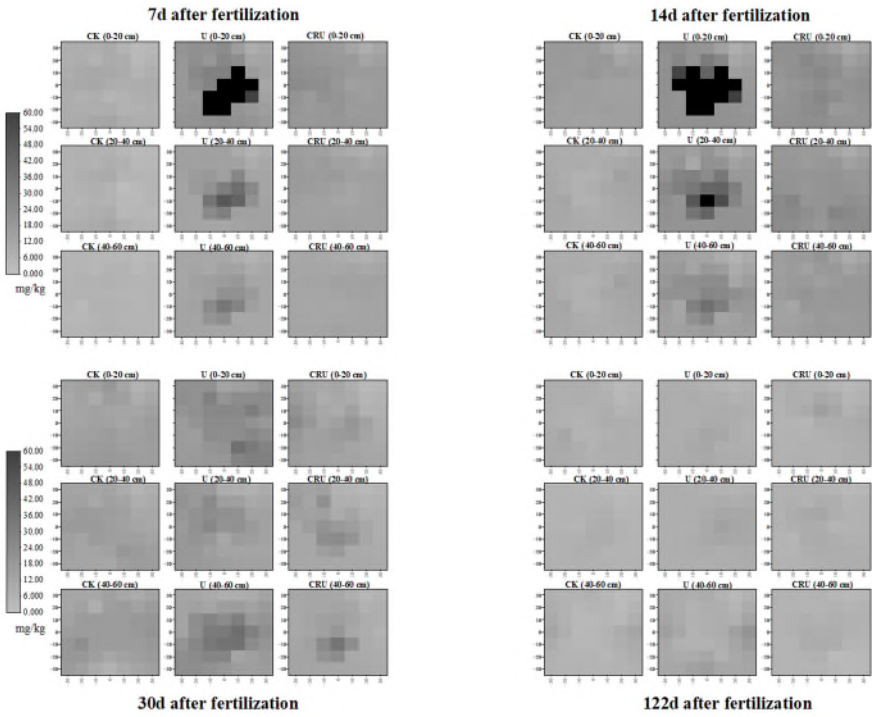


Fig. 6 Spatial distribution characteristics of Nmin after fertilization with different treatments

Notes: Unit: mg/kg. CK: No N fertilizer input; U: Application of conventional urea; CRU: Application of controlled release urea.

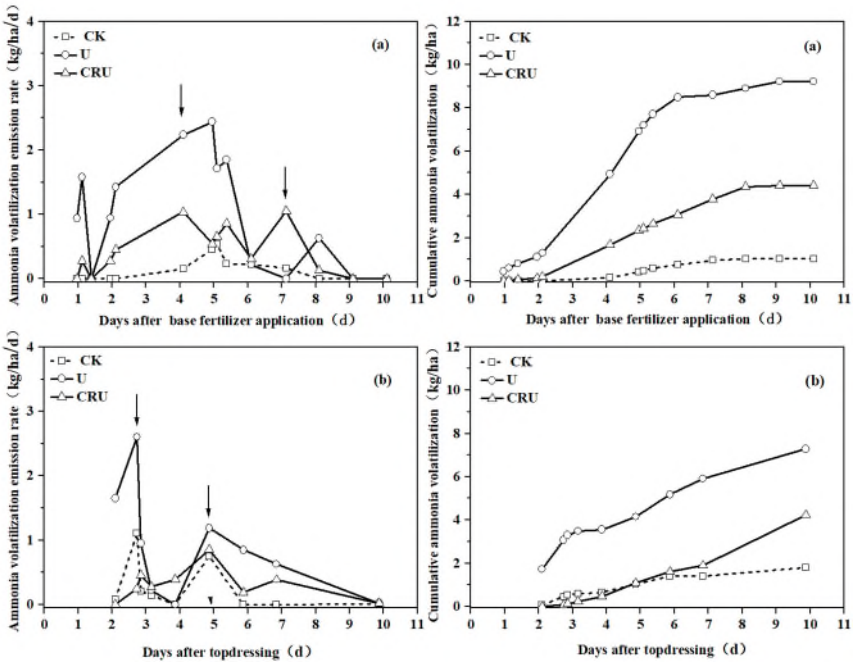


Fig. 7 Soil AV emission rate (a) and cumulative AV_{losses} (b) of different treatments after base fertilization and after top-dressing fertilization

Notes: CK: No N fertilizer input; U: Application of conventional urea; CRU: Application of controlled release urea.

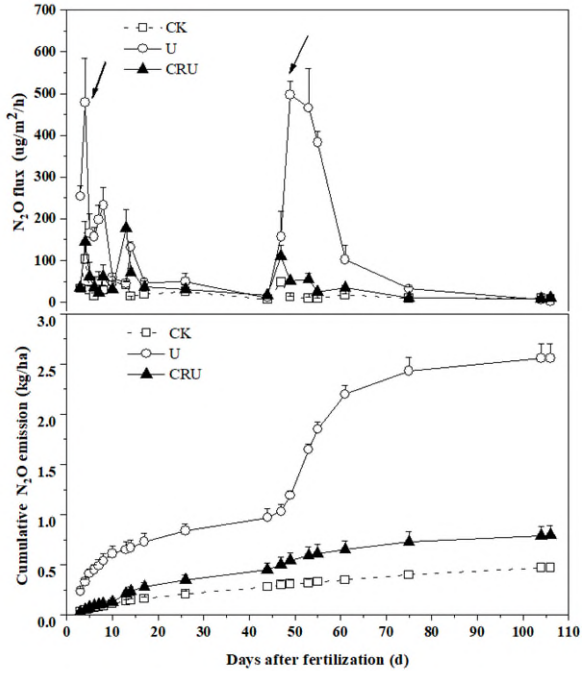


Fig. 8 N_2O flux and cumulative N_2O emissions of different treatments after fertilization

Notes: CK: No N fertilizer input; U: Application of conventional urea; CRU: Application of controlled release urea.

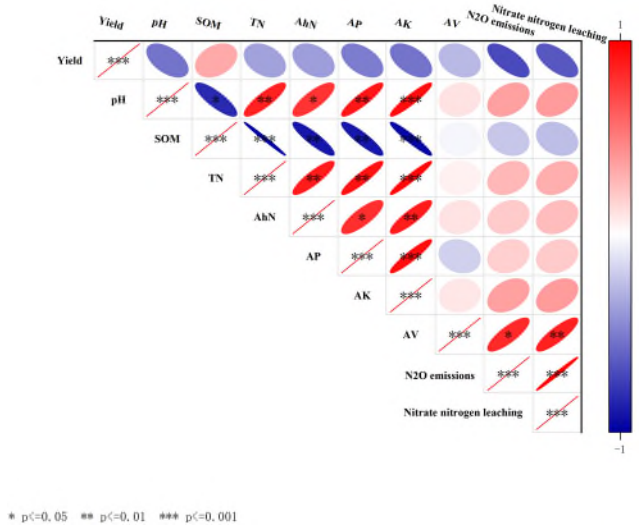


Fig. 9 Correlation analysis of soil physical and chemical properties, nitrogen loss pathways and yield

Notes: U: Application of conventional urea; CRU: Application of controlled release urea. pH: pH; SOM: Soil Organic Matter; TN: Total Nitrogen; AhN: Alkaline Hydrolyzable Nitrogen; AP: Available Posphorus; AK: Available Ptassium; AV: Ammonia Volatilization."NS", not significant; "*", significant at $P<=0.05$; "**", significant at $P<=0.01$ and "***", significant at $P<=0.001$.

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