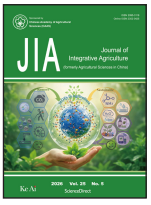
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RESEARCH ARTICLE

Optimizing nitrogen management for higher grain yield and nitrogen use efficiency in summer maize by coordinating the N supply–demand balance

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Highlights

- Early-maturing maize hybrids have lower N uptake than late-maturing summer hybrids.
- Either controlled-release urea (CRU) or the split application of urea (SAU) can achieve N supply-demand balance in early-maturing hybrids.
- CRU combined with SAU can achieve N supply-demand balance in late-maturing hybrids.

Abstract

Characterizing the N uptake and utilization of different maize hybrids is essential for optimizing N application and increasing the profits from maize production. Research trials were conducted with controlled-release urea (CRU) as a base fertilizer (TC) and urea split application in one (T1), two (T2), or three (T3) stages to evaluate the effects on N uptake, N use efficiency (NUE), and yield using the ^{15}N tracer technique and two maize hybrids: DH518 (a mid-early-maturing hybrid) and DH605 (a late-maturing hybrid). According to the results, compared with urea, CRU as a base fertilizer and urea split applications in two and three stages significantly increased grain yield and NUE while reducing environmental N loss. Compared with T1, the grain yields of the TC, T2, and T3 treatments were respectively increased by 11.1, 9.8, and 11.7% in DH518 and by 16.4, 15.7, and 22.9% in DH605. Regression analysis showed that the grain yield of DH518 displayed a bilinear trend with an initial rapid increase and then a slow increase with increases in post-anthesis N accumulation, total N accumulation, N recovery efficiency, and N nutrition index (NNI). By contrast, DH605 consistently showed a linear regression relationship with a rapid increase. The crop recovery N efficiency (CRN) values in the T3 treatment for urea applied at the sowing stage and as topdressing at the 9th-leaf stage (V9) in DH518 were 60.0 and 62.4% higher than under topdressing at the tasseling stage (VT) stage, respectively, while the CRN values of urea topdressing at the V9 and VT stages in DH605 were 37.7 and 37.1% higher than when applied at the sowing stage, respectively. The higher pre-anthesis N demand and shorter growth period of DH518 maintained the N supply–demand balance, resulting in the NNI (NNI≥0.988) falling within the range of a low yield increase under the T2 and TC treatments, while the N status of DH605 plants only reached optimal levels in the T3 treatment. Therefore, a three-stage split application of urea or applying CRU as a base fertilizer and topdressing with urea in the later growth stages is recommended for obtaining an optimal yield in mid-late-maturing hybrids. In addition, for mid-early-maturing hybrids, applying CRU or reducing the number of split applications, e.g., a two-stage split application, can ensure an adequate N supply in the later growth stages and increase production, and thus profits.

Keywords: summer maize, ^{15}N tracer technique, N use efficiency, N nutritional index, grain yield

1. Introduction

The idea that applying more N can significantly enhance crop yield has been widely supported over the past few decades. However, recent studies suggest that despite the increase in fertilizer application, the rate of crop yield growth has not been as high as expected, primarily due to the excessive use and improper timing of fertilization (Sela 2018; Yu *et al.* 2020). Optimal nutrient management practices are based on

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the 4R principles (right form, right place, right time, and right rate), guidelines that are designed to maximize the alignment between plant requirements and the nutrient supply (Fixen 2020). Among the promising on-field urea management methods that have been explored, a split application of fertilizers (applying the required N in predetermined proportions at different stages of crop growth) can better match the N supply–demand relationship of the crops and is considered one of the most effective techniques (Sahar *et al.* 2012; Yang *et al.* 2014; Fernandez *et al.* 2020). For example, in maize, the N fertilization management patterns of splitting into three or four applications are often used to achieve higher yields. Unfortunately, due to the immaturity of mechanical topdressing technology, N supplementation in the later stages is often conducted manually, which limits the application of staged fertilization (Geng *et al.* 2015). However, the implementation of split fertilizer application in global agricultural production has achieved greater acceptance with the promotion of integrated water and fertilizer technology.

The split application of urea has been shown to increase yields and N use efficiency (NUE) (Wang *et al.* 2016; Wu *et al.* 2019; Motasim *et al.* 2022). Although this technology is widely applied and promoted in various crops such as rapeseed, wheat (Grant *et al.* 2012), rice (Chen *et al.* 2015), and maize (Deng *et al.* 2023), there are currently no unified standards for the timing or rate of split application of urea (SAU) in practical production. To reduce the cost of field fertilizer management, the same N application pattern and rate (Chen *et al.* 2015; Zhang *et al.* 2022) are often adopted for hybrid crops. With the continuous decline in the global agricultural labor force, the issues of production costs and efficiency have become increasingly serious in maize production (Hamilton 2021; Nye 2021). As a new type of fertilizer, controlled-release urea (CRU) can coordinate the N supply and demand balance by altering the release rate of N (Shoji *et al.* 2001). Unlike SAU, applying CRU at sowing can significantly reduce the labor input (Ke *et al.* 2018). Due to its high cost, CRU was not widely accepted by growers in the past, but the continuous emergence of new low-cost polymer-coated materials in recent years has revitalized its application (Gao *et al.* 2015; Duan *et al.* 2016). However, due to differences in maize growth periods, fertilizer release times, and the specific N requirements of hybrids, the N supply–demand relationship between a given CRU regimen and different summer maize hybrids may break down, resulting in a negative impact on yield (Farmaha and Sims 2013). Therefore, clarification of the fertilization requirements of different hybrids is urgently needed so they can be matched with more suitable forms of CRU.

Previous studies have reported no differences in N uptake among maize hybrids with the same growth period (Ali *et al.* 2023). However, those studies focused more on mid-late-maturing hybrids in pursuit of high yields, with less attention being given to the N requirements of early-maturing hybrids. To meet the requirements of fully mechanized production, mid-late-maturing hybrids with high yield potential will gradually be replaced by mid-early-maturing hybrids that are suitable for mechanized harvesting (Li *et al.* 2021). Nevertheless, are the fertilization requirements for distinct maize hybrids in different growth stages the same; and can a unified N fertilizer management technique be adopted? The answers to these questions remain unclear. Based on studies of the growth and development characteristics of distinct maize hybrids in different growth stages conducted by our research team, we hypothesized that (1) the N application pattern of a three-stage split application of urea to provide a sufficient supply of N in the later stages of growth in late-maturing hybrids will not meet the higher N requirements of the early-maturing hybrids in the exponential stage of growth; (2) the shortened growth period of early-maturing maize hybrids may reduce the N requirements during the grain-filling stage, so that the yield with CRU as a base fertilizer or a two-stage split application of urea will be equivalent to that of a three-stage split application of urea, and (3) CRU as a base fertilizer or a two-stage split application of urea will not meet the N demand of late-maturing hybrids in the later growth stages, and thus the yield will be significantly lower than under a three-stage split application of urea.

Field experiments were conducted in 2019 and 2020 in addition to a micro-plot experiment with ^{15}N fertilizer in 2019 to test these hypotheses by examining the yield, NUE, and N uptake properties of mid-early-maturing and late-maturing hybrids, with the ultimate goal of designing more appropriate N management measures for different maize hybrids. The experimental objective mainly involved identifying the optimal N application patterns for different hybrids, thereby providing a deeper understanding of N fertilizer management to enhance summer maize production.

2. Materials and methods

2.1. Experimental site and experimental design

The experiment was conducted during 2019 and 2020 at the Huang-Huai-Hai Maize Innovation Center in Tai'an, China. According to the U.S. Classification of Typic Paleustalfs, the soil type was brown loam. Prior to the experiment, soil samples were collected (0–20 cm deep) and the following soil properties were measured: organic matter, 14.2 g kg^{-1}; total N, 1.1 g kg^{-1}; rapidly available P, 52.1 mg kg^{-1}; and rapidly available K, 83.2 mg kg^{-1}. The region has a temperate continental monsoon climate, with accumulated temperature during the summer maize growing season (June 10th to October 1st) ranging from 1,789.9°C to 1,696.8°C and rainfall of 342.4–805.8 mm (Appendix A).

The experiment adopted the locally planted maize hybrids Denghai 518 (DH518, with a growth period of 105 days) and Denghai 605 (DH605, with a growth period of 115 days) that display significant differences in their growth stages. Both field and microplot experiments were designed for the study. Five N supply treatments were designed according to the local farmers' practices and the N demand characteristics of summer maize: a zero-N treatment (T0), controlled-release urea (TC) or normal urea (T1) as a base fertilizer, and a normal urea split application in two (40% at sowing and 60% at the V9 stage, T2) and three (30% at sowing, 50% at the V9 stage and 20% at the tasseling stage (VT) stage, T3) stages (Appendix B). The planting density was 75,000 plants

ha^{-1} with row spacing of 60 cm. The experimental area of each plot was 30 m^2 (10 m in length and 3 m in width), with four replicates per plot. CRU (N:P_2O_5:K_2O ratio of 28:7:9) was provided by the Maoshi Company, Shandong Province, China. Each plot had the fertilizer applied as 456.5 kg ha^{-1} urea (46% N), 375.0 kg ha^{-1} calcium superphosphate (12% P_2O_5), and 112.5 kg ha^{-1} potassium chloride (60% K_2O). The phosphate and potassium fertilizers were applied as base fertilizers. The water supply was sufficient during growth, and plant diseases, insect pests, and weeds were controlled to prevent yield losses.

To investigate the effects of split N application on the fate of ^{15}N in different hybrids, a microplot experiment with ^{15}N fertilizer was established in 2019. Cylindrical soil column cultivation was adopted to minimize normal root growth and development restrictions. Polyvinyl chloride (PVC) boards were rolled into cylinders with a diameter of 36.5 cm and a height of 120 cm. These were placed in soil pits 110 cm deep 30 d before sowing. The area around the column was filled with soil, and irrigation was carried out before sowing so that the soil condition of the column was consistent with that of the field as much as possible. Three plump corn seeds were selected for sowing with singling at the V1 stage. The ^{15}N-labelled urea application pattern is shown in Appendix B. The ^{15}N proportion of the applied urea was 10.18%.

2.2. Measurements

Dry matter accumulation (DMA) Five representative plants with consistent growth were selected from each plot at the tasseling stage (VT) and physiological maturity stage (R6). All plants were divided into leaf, stem (including sheath), husk, and grain. The samples were dried at 105°C for 30 min in an oven, then dried at 80°C until a constant weight was obtained. Each organ was ground using an FZ102 miniature plant crusher (Tianjin Test Instrument Co., Ltd.) for further analysis.

Fertilizer ^{15}N fate After drying, the crushed plant samples were passed through a 200-mesh sieve, and 4 mg plant samples were accurately weighed and placed in a tin capsule. Plant N content and ^{15}N abundance were analyzed using an isotope mass spectrometer (Isoprime100, Elementar vario MICRO cube, UK). The fertilizer ^{15}N recovery efficiency of plants and soil from the microplots was calculated as described by Liu *et al.* (2005).

Nitrogen use efficiency and nitrogen nutrition index All samples were digested with H_2SO_4-H_2O_2, and the total N content of samples was determined using an AA3 continuous flow analyzer. The NUEs of agronomic N use efficiency (AEN) and apparent N recovery efficiency (REN) were calculated as described by Chen *et al.* (2018). The critical N concentration (N_c) and N nutrition index (NNI) were calculated as described by Lemaire *et al.* (2009) and Liang *et al.* (2018).

Grain yield At the maturity stage, the ears from three rows in the middle of each plot were harvested, with three random replications per plot, and 30 ears were harvested per replicate. The grain yield was determined based on a 14% maize kernel moisture content.

Statistical analyses Microsoft Excel (Microsoft, Redmond, WA, USA) and SPSS 21.0 (IBM Corporation, Armonk, NY, USA) were used for data analysis. Simple linear regression analysis was used to determine the correlations between grain yield and various other factors. ANOVA was used to evaluate the effects of hybrid, N application pattern, and their interaction on grain yield, DMA, N accumulation, N harvest index (NHI), NNI, AEN, and REN. A least significant difference test with a 0.05 probability level was used to determine significant differences between the means. SPSS was used to calculate Pearson correlation coefficients.

3. Results

3.1. Grain yield and dry matter accumulation

The responses of yield to N application patterns differed significantly among the mid-early- and late-maturing hybrids. The yields for each treatment of DH518 were in the order T3≈TC≈T2>T1, and in DH605 the order was T3>TC≈T2>T1 (Fig. 1). Except for the T1 treatment, the yields of DH518 in all other treatments were significantly lower than in DH605 under the same treatment. There was no significant difference in yield between the two hybrids under the TC or T2 treatments, with increases of 9.6–12.6% and 8.3–11.3% in DH518 and 14.9–18.0% and 14.2–17.1% in DH605. The yields of the DH518 TC and DH518 T2 treatments did not differ significantly from that of the DH518 T3 treatment, while the yield of the DH605 T3 treatment was significantly higher, by 5.1–6.0% and 5.9–6.6% compared with the DH605 TC and DH605 T2 treatments, respectively. The results were consistent over the two years (Fig. 1).

The DMA values of DH518 in each treatment at R6 were in the order T3≈TC≈T2>T1, while in DH605 the order was T3>TC≈T2>T1 (Appendix C). The dry matter accumulation of each treatment in DH518 was significantly lower than in DH605. The dry matter accumulation under CRU as a base fertilizer was significantly increased, by 13.5–14.9% in DH518 and by 14.7–20.2% in DH605, compared with urea as a base fertilizer. The dry matter accumulation significantly increased with an increase in the number of urea split applications. There was no significant difference in dry matter accumulation between the DH518 T2 and DH518 T3 treatments, while the dry matter accumulation in the DH605 T3 treatment was significantly increased by 4.7–4.8% compared with the DH605 T2 treatment (Appendix C).

3.2. Nitrogen accumulation, NHI, and N uptake characteristics

N accumulation and NHI The mid-early-maturing and late-maturing hybrids showed similar N accumulation responses to the N application patterns (Appendix D). During the two-year R6 stage, the N accumulation from the basal application of CRU was significantly higher than under the basal application of urea and increased significantly with the number of urea split applications. The N accumulation in DH518 showed a smaller increase than in DH605. During the VT stage, the N accumulation in T2 was the highest for both hybrids, and N accumulation in the TC treatment was not significantly different from the T1 treatment, while both were significantly higher than in the T3 treatment. The N accumulation in

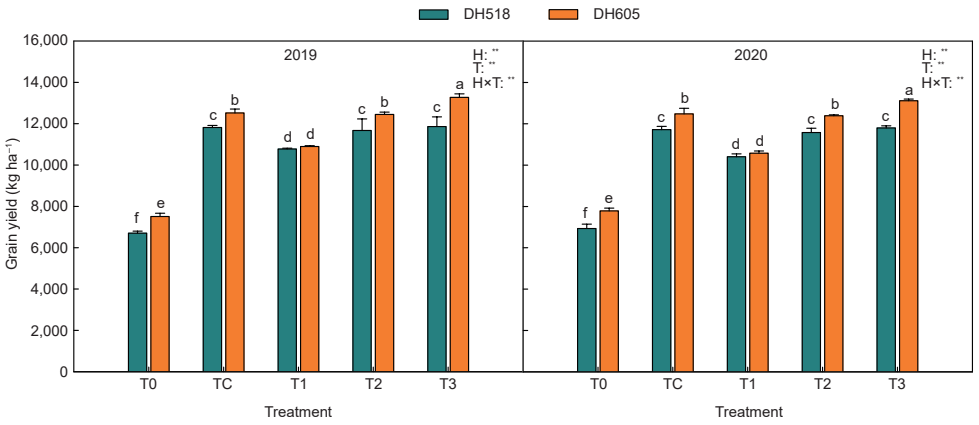


Fig. 1 Effects of optimal nitrogen management on the grain yields of different maize hybrids. DH518, Denghai 518; DH605, Denghai 605. T0 is the zero-N treatment, TC and T1 are controlled-release urea (CRU) and urea as a base fertilizer, respectively; and T2 and T3 are urea split applications in two and three stages, respectively. H, hybrid; T, N split application. Bars mean SD (n=3). Different letters beside the bars indicate significant differences (P<0.05). **, significant at P<0.01.

DH518 T1 was significantly higher than in DH605 T1, while the N accumulation levels in DH518 and DH605 were similar to the other treatments.

Optimized N management significantly improved the NHI of maize. The performance levels of NHI in different treatments for the two hybrids were in the order T3>TC=T2>T1, with the NHI of DH518 significantly lower than in DH605. The increases in the two hybrids under the T3 treatment compared with T1 were 4.4–4.6% in DH518 and 4.1–4.8% in DH605 (Appendix D).

Relationships between grain yield and N accumulation and NHI The regression analysis showed significant correlations between grain yield and N accumulation during maturity, grain yield and pre-anthesis N remobilization amount (PRNA), and grain yield and post-anthesis N accumulation amount (PNAA), as well as between grain yield and NHI for both hybrids. Grain yield was negatively correlated with PRNA and positively correlated with the other traits. The grain yield of DH518 was bilinearly correlated with both TN and PNAA. The grain yield of DH518 increased significantly with TN, but at TN≥212.22 kg ha^{-1}, the slope (k) of the linear regression equation decreased, meaning that the rate of increase in grain yield slowed. At a PNAA≥90.95 kg ha^{-1}, the slope (k) of the linear regression between grain yield and PNAA decreased such that the yield tended to stabilize (Fig. 2).

Sources of plant N accumulation and crop recovery N efficiency (CRN) During the VT stage, there was no significant difference in soil N uptake between the two hybrids, with DH 518 accumulating significantly more N from the fertilizers than DH605. Accordingly, the CRN of DH518 was significantly higher than that of DH605. During the R6 stage, both hybrids showed similar soil N uptake responses to the N application patterns, where N uptake increased with the number of N split applications. The fertilizer N uptake in the DH518 T3 treatment did not differ significantly from the DH518 T2 treatment, but N uptake was significantly higher than in the DH605 T2 treatment than in the DH605 T3 treatment (Fig. 3).

The CRN of the N split application treatments at each N application stage were calculated, and the CRN of both hybrids increased significantly with the number of N split applications (Appendix E). For example, compared with the T1 treatment, the CRN of the N application at the sowing stage in the DH605 T2 and DH605 T3 treatments increased significantly by 15.6 and 26.3%, respectively. The CRN variation trends of the two hybrids treated with T3 differed among the fertilization stages. The CRN values of N applied at the sowing stage and topdressing at the V9 stage in DH518 were 60.0 and 62.4% higher than under topdressing at the VT stage, respectively, while the CRN values of N topdressing at the V9 and VT stages in DH605 were 37.7 and 37.1% higher than when applied at the sowing stage, respectively (Appendix E).

3.3. Nitrogen nutrition index and nitrogen use efficiency

NNI The plant N status can be quantitatively evaluated using NNI. A value of NNI>1.0 signifies an oversupply of N, while NNI<1.0 indicates N deficiency, and NNI close to 1.0 suggests a moderate N application level for the crop. There were significant differences in the response of NNI to N application patterns between the mid-early-maturing and late-maturing hybrids (Appendix F).

At the VT stage, the NNI values of both hybrids in the TC, T1, and T3 treatments were slightly greater than or equal to 1, indicating the optimal N status of the plants. However, the NNI values of both hybrids in the T2 treatment were greater than 1, indicating an N surplus in the plants. At the R6 stage, the NNI of the DH518 T3 treatment was greater than 1, indicating an excessive N supply. The NNI values of the DH518 TC, DH518 T2, and DH605 T3 treatments were close to 1, indicating the optimal N status of the plants. However, the NNI values of the remaining treatments were all less than 1, indicating an N deficiency in the plants (Appendix F).

Finally, the urea-based application of 456.5 kg ha^{-1} (46% N) did not meet the needs of normal plant growth, while the split application of urea in two or three stages in DH518 or the split application of urea in three stages in DH605 was able to

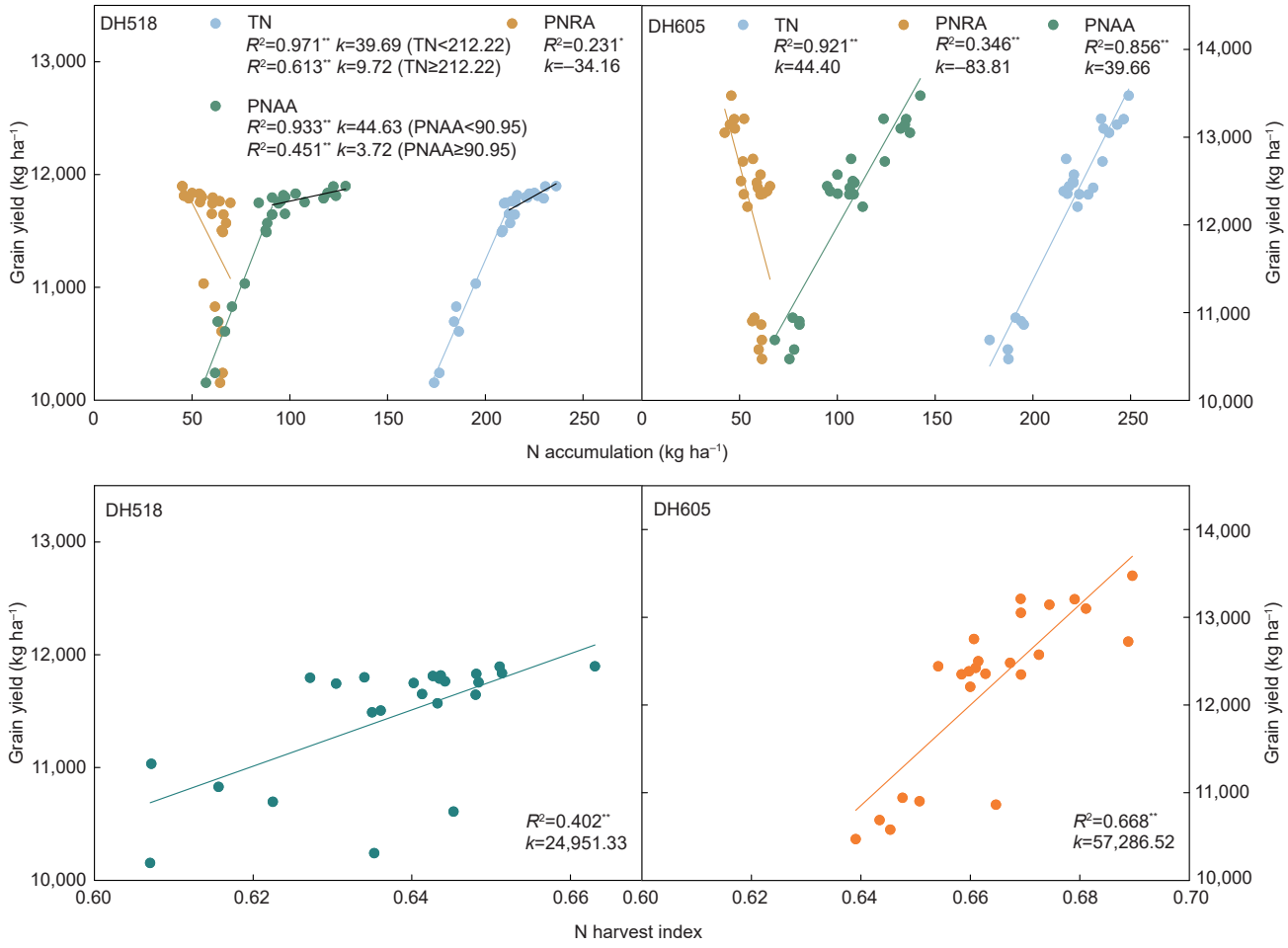


Fig. 2 Regressions of grain yield and N accumulation and N harvest index. DH518, Denghai 518; DH605, Denghai 605. TN, total N accumulation; PNRA, pre-anthesis N remobilization amount; PNAA, post-anthesis N accumulation amount. The parameter *k* is the slope of a linear equation, and R^2 is the coefficient of determination, which indicates regression strength, with *, $P<0.05$ and **, $P<0.01$.

meet the requirements for normal plant growth.

NUE In the two years, the AEN values of DH518 were in the order T3≈TC≈T2>T1, while DH605 exhibited the order T3>TC≈T2>T1 (Appendix G). There were no differences in AEN between the TC and T2 treatments for either hybrid. The AEN of the DH518 T1 treatment was significantly increased by 14.2–15.8% compared with the DH605 T1 treatment, whereas the AEN of the DH518 T3 treatment significantly reduced by 7.6–9.4% compared with the DH605 T3 treatment. The two hybrids showed similar responses in REN to N application, with increases in REN as the number of N split applications increased. The REN of the DH518 T3 treatment was significantly reduced by 11.2–12.7% compared with the DH605 T3 treatment, while the REN values in the other treatments of both hybrids did not differ (Appendix G).

Relationships between grain yield and NNI and NUE The regression analysis showed that the two hybrids exhibited positive correlations between grain yield and NNI at maturity, grain yield and AEN, and grain yield and REN. The correlation between grain yield and NNI at the VT stage was not significant. There were bilinear regression relationships between grain yield and NNI at the R6 stage and between the grain yield and REN of DH518. The grain yield of DH518 significantly increased with an increase in NNI at the R6 stage, but for NNI≥0.988 and REN≥35.3%, the slope (*k*) of the linear regression equation decreased, meaning that the increase in grain yield slowed. The slope (*k*) of the linear regression equation for DH605 was greater than that for DH518 (Fig. 4).

3.4. The fate of fertilizer ^{15}N

The fate of fertilizer ^{15}N in the two hybrids differed according to the N application pattern. The SRN of DH518 significantly increased with an increase in the number of N split applications. The CRN did not differ between the DH518 T2 and DH518 T3 treatments, with both being significantly higher than in the DH518 T1 treatment. No difference in SRN was observed between the DH605 T2 and DH605 T3 treatments, and the values of both were significantly lower than in the DH605 T1 treatment. The CRN of DH605 significantly increased with an increase in the number of split N applications. The ELN of DH605 was lower than that of DH518, and the ELN values of both hybrids decreased significantly with an increase in the number of N applications (Fig. 5).

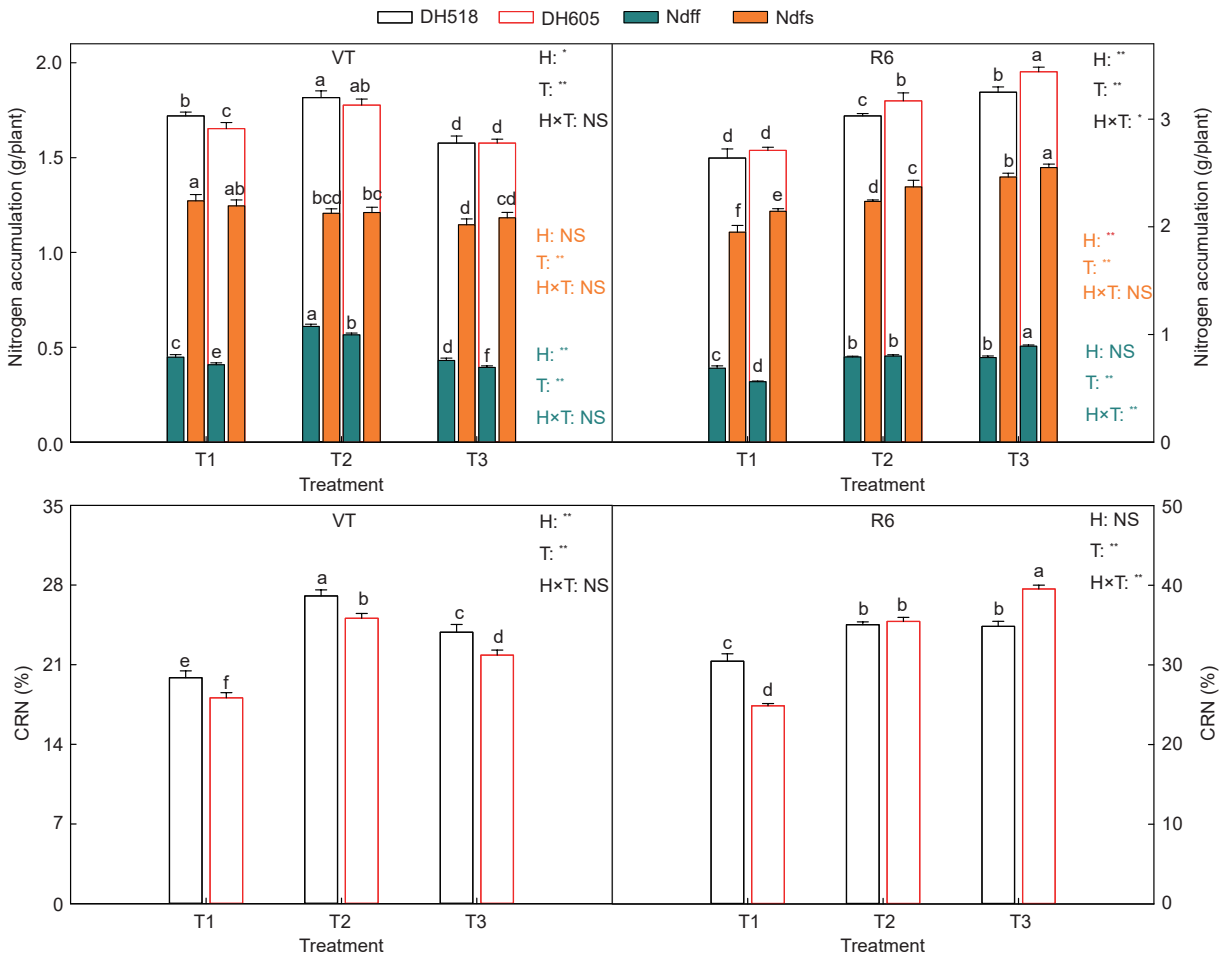


Fig. 3 Effects of optimal nitrogen management on N sources and crop recovery N efficiency (CRN) of different maize hybrids in a microplot experiment. DH518, Denghai 518; DH605, Denghai 605. Ndff, N derived from fertilizer; Ndfs, N derived from soil. VT, anthesis stage; R6, physiological maturity stage. T1 is urea as a base fertilizer; T2 and T3 are urea split applications in two and three stages, respectively. Different letters beside the bars indicate significant differences (P<0.05). H, hybrid; T, N split application; *, NS and **, significant at P<0.05, not significant at P<0.05 and significant at P<0.01, respectively.

3.5. Economic costs

The difference in other costs between the two hybrids was due to variations in harvesting methods: DH518 used mechanical grain harvesting, while DH605 used mechanical ear harvesting and manual drying. The harvest cost of DH605 was significantly higher than that of DH518, by 1,125 CNY ha^{-1} (Appendix H). The production costs of different N application patterns for both hybrids were in the order of T3>TC≈T2>T1. The profit margins for each treatment were in the order DH605 T3>DH605 TC≈DH605 T2≈DH518 TC≈DH518 T2>DH518 T3>DH518 T1>DH605 T1 (Table 1). The profit margin of the DH605 T3 treatment was the highest, with no significant differences between the TC and T2 treatments for either hybrid. The profit margin of the DH518 TC treatment was significantly higher than for the DH518 T3 treatment, by 5.0%, and the profit for the DH605 TC treatment was significantly lower than for the DH605 T3 treatment. The profit margin of the DH518 T3 treatment was significantly lower than for the DH605 T3 treatment, by 9.2%, and the profit from the DH518 T1 treatment was significantly higher than for the DH605 T1 treatment, by 8.4% (Table 1).

4. Discussion

4.1. Optimal nitrogen management for the regulation of yield in hybrids with different growth durations

Many studies have shown that increasing the rate of N application is not a sustainable approach for improving crop yields (Ahmad *et al.* 2023; Zhang *et al.* 2023; Fang *et al.* 2026). The emergence of split fertilization technology has provided a means of effectively balancing the relationship between yield and N application rate. This study demonstrated that N split application significantly increases grain yield compared with urea-based application (Fig. 1). High crop yields are predicated on dry matter accumulation, while higher dry matter accumulation is based on plant nutrient uptake (Watt *et al.* 2003; Dordas *et al.* 2012). Plant biomass and N content are positively correlated during vegetative development (Ciampitti and Lemaire 2022). Like the dry matter distribution, most of the N accumulated in the maize plant is distributed to grains, with the distribution ratio ranging from 60 to 80% (Stevens *et al.* 2005; Rimski-Korsakov *et al.* 2012). An increase in the N uptake ratio in the early growth stage will increase N accumulation in

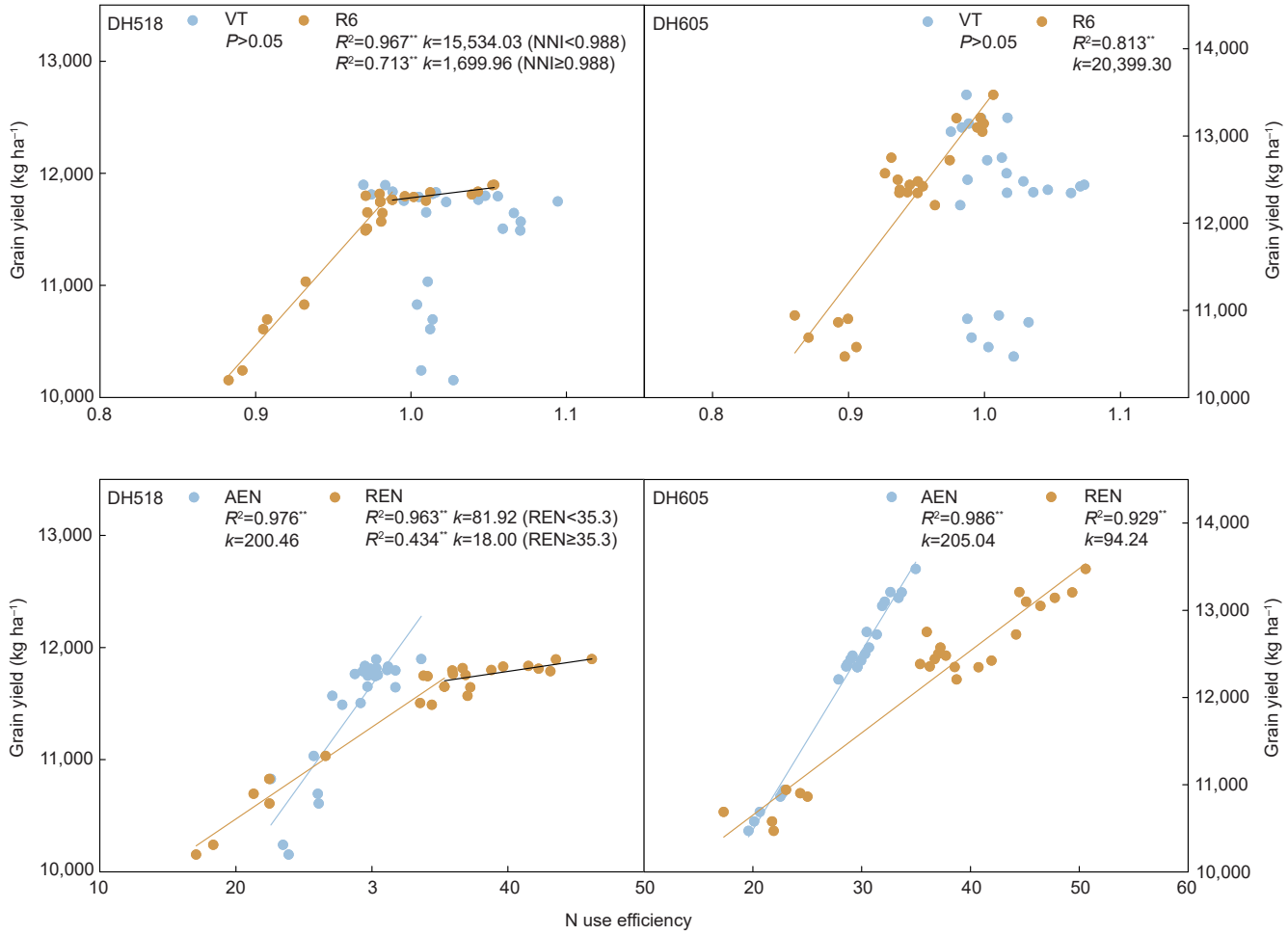


Fig. 4 Regressions of grain yield and nitrogen nutrition index (NNI) and N use efficiency (NUE). DH518, Denghai 518; DH605, Denghai 605. VT, anthesis stage; R6, physiological maturity stage; AEN, agronomic N use efficiency; REN, N recovery efficiency. The parameter *k* is the slope of a linear equation, and R^2 is the coefficient of determination, which indicates regression strength, with **, $P<0.01$.

vegetative organs and reduce its distribution to grains (Yang *et al.* 2011). The proportion of accumulated N in maize plants that is distributed to the grains directly affects grain yield (Wang *et al.* 2020; Liu *et al.* 2021). Our results indicated that N split application significantly increased N accumulation and NHI in both hybrids, with a larger N increase and higher yield in DH605 compared with DH518. Potential yields, and hence crop N requirements, are largely determined within 30 d before and after silking (Cakir *et al.* 2004; Maddonni *et al.* 2006; Niemeyer *et al.* 2021). Up to the silking stage, the yield of late-maturing hybrids remains responsive to N application (Scharf *et al.* 2002). In this study, N application in multiple stages significantly increased REN and the PNAA and TN of the two hybrids (Appendices D and G). The grain yield of DH518 showed a bilinear regression relationship with PNAA and TN, and the N accumulation in the DH518 T3 treatment, which was significantly higher than in the T2 treatment, while no difference in yield was observed between the DH518 T3 and DH518 T2 treatments (Fig. 1). This indicates that the N accumulation of PNAA and TN in the DH518 T2 treatment was within the range of a slow yield increase (TN≥212.22, PNAA≥90.95), and further increasing the number of N split applications would not significantly increase the yield. The main reason is that when urea was applied in two stages, the NNI of plants in the R6 stage was close to 1, indicating the optimal N status of the plants. Under the split application of urea in three stages, the NNI of plants in the R6 stage was greater than 1, indicating an N surplus in the plants. The grain yield of DH605 showed linear relationships with both PNAA and TN, even with three applications of N, which confirms that there was a significant increase in yield. Therefore, for mid-early-maturing summer maize hybrids such as DH518, relying solely on N split application to achieve greater yield is limited. In the future, comprehensive management that combines other agronomic measures such as increasing plant density and improving soil physicochemical properties is needed to further increase the yield. For late-maturing summer maize hybrids such as DH605, there is significant untapped yield potential under the N split application.

Compared with urea, CRU as a base fertilizer can significantly improve grain yield and N use efficiency and reduce N loss (Xu *et al.* 2021). However, few studies have compared CRU as a base fertilizer and SAU in hybrids with different growth durations. According to the yield responses

of the different treatments and the values of DMA, N accumulation, and AEN in the various N application patterns, the performance of DH518 TC was equivalent to those of DH518 T2 and DH518 T3. However, the plant performance of DH605 TC was consistent with that of DH605 T2, which was significantly lower than DH605 T3. With the widespread application of CRU as a base fertilizer in maize production, mid-early-maturing maize hybrids can better realize their yield potential, but late-maturing hybrids need topdressing with urea in the later growth stage or the application of CRU of higher quality (such as having a longer controlled release time or better coating quality) to ensure a sufficient N supply and obtain a higher yield.

4.2. Effects of optimal nitrogen management on nitrogen use efficiency in hybrids with different growth durations

AEN can be altered by N fertilizer management strategy (type of input, timing, method, and amount of application), crop type, and variety (Zavattaro *et al.* 2015; Montemurro and Diacono 2016; Saudy *et al.* 2018). In this study, N split application enhanced the AEN of maize, but the AEN performance differed between the two hybrids (Appendix G). For instance, DH605 showed a significantly higher AEN when N was applied in three stages compared with two stages, whereas DH518 did not exhibit further increases in AEN with three applications. A split N application enhanced the REN of maize (Appendix G), consistent with studies by Wu *et al.* (2019) and Motasim *et al.* (2022). The CRN from each application was calculated to measure the contrasting responses of REN to three-split applications between the two hybrids. DH518 absorbed a significantly higher proportion of N from the urea applied at the sowing stage and topdressing at the V9 stage compared with topdressing at the VT stage, while DH605 absorbed a significantly higher proportion of N from topdressing urea at the V9 and VT stages compared with application at the sowing stage. This suggests that DH518 had a higher pre-anthesis N uptake with declining post-anthesis N demand, while DH605 maintained a higher N demand, even at the VT stage compared with the VE–V9 stage. Compared with DH605, the higher pre-anthesis N uptake of DH518 increased the ^{15}N recovery rate under the T1 treatment (Fig. 5), increased the amount of additional grain harvested with urea as a base fertilizer (Fig. 1), and improved the AEN (Appendix G). Research by Mueller and Vyn (2018) indicated that reducing the proportion of early N application reduced the ability of plants to recover N during the vegetative growth period. In this study, N deficiency was not observed under any treatment of either hybrid at the VT stage, but there were different responses at the R6 stage. The lower post-anthesis N demand of DH518 resulted in an optimal N nutrition status for plants in the DH518 T2 and DH518 TC treatments at the R6 stage, while a slight N surplus was observed in the DH518 T3 treatment. Plants in the DH605 group exhibited poorer N status, except for the T3 treatment, which ultimately affected yield. Pre-seeding N application may lead to N losses ranging from 20 to 70% due to the crops' inability to rapidly absorb the N, but N application during periods of crop demand can mitigate N losses (Mueller and Vyn 2018; Kosola *et al.* 2023; Song *et al.* 2024). Increasing the frequency of N application significantly reduced environmental loss N (ELN), but the reasons for the reduction differed between the two hybrids. Compared with DH518 T2, the CRN of DH518 T3 remained the same, while soil residual N (SRN) increased, thereby reducing the ELN. Conversely, DH605 T3 significantly increased the CRN, reducing the ELN (Fig. 5).

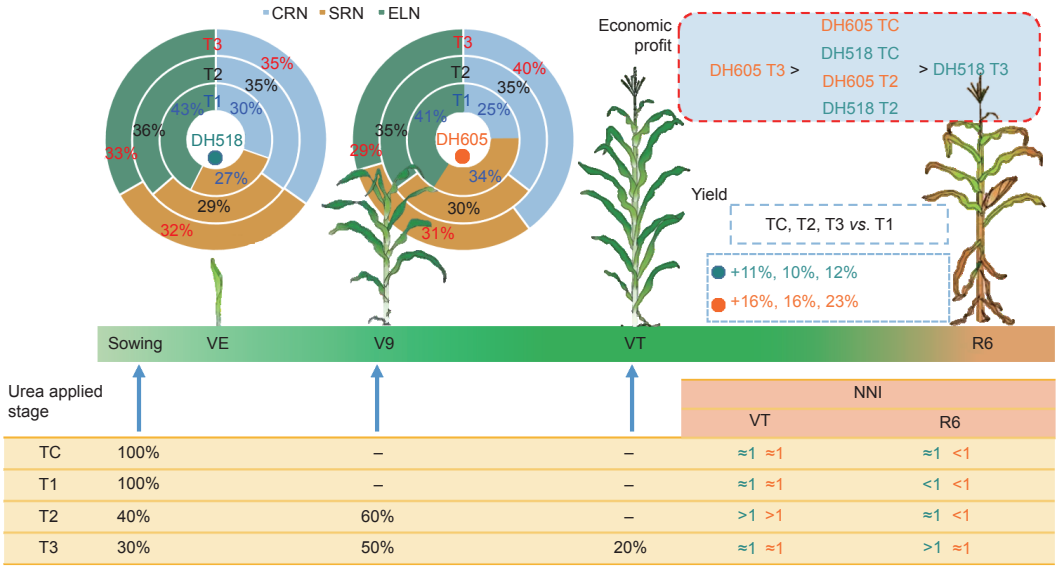


Fig. 5 Effects of optimal nitrogen management on nitrogen nutrition index (NNI), grain yield, economic profit and the fate of fertilizer ^{15}N for different maize hybrids. DH518, Denghai 518; DH605, Denghai 605. CRN, crop recovery N efficiency; SRN, soil ^{15}N residual; ELN, environmental ^{15}N loss. TC and T1 are controlled release urea and urea as a base fertilizer, respectively; T2 and T3 are urea split applications in two and three stages, respectively. VE, emergence stage; V9, the 9th-leaf stage; VT, tasseling stage; R6, physiological maturity stage.

Table 1 Effects of optimal nitrogen management on the economic profit of summer maize (CNY ha^{-1})

Hybrid	Treatment[1)]	Gross return	Fertilizer cost	Topdressing cost	Other costs[2)]	Economic profit
Denghai 518	T0	9,215±77 f	–	–	4,500	4,715±77 f
	TC	20,003±144 c	3,060	–	4,500	12,443±144 b
	T1	18,007±151 d	2,259	–	4,500	11,247±151 d
	T2	19,762±647 c	2,259	750	4,500	12,253±647 bc
	T3	20,110±351 c	2,259	1,500	4,500	11,851±351 c
Denghai 605	T0	10,609±104 e	–	–	5,625	4,984±104 f
	TC	21,250±330 b	3,060	–	5,625	12,565±330 b
	T1	18,257±113 d	2,259	–	5,625	10,373±113 e
	T2	21,112±109 b	2,259	750	5,625	12,478±109 b
	T3	22,432±138 a	2,259	1,500	5,625	13,048±138 a

[1)] T0 is the zero-N treatment; TC and T1 are CRU and urea as a base fertilizer, respectively; and T2 and T3 are urea split applications in two and three stages, respectively.
[2)] Other costs include sowing, seeds, field management, pesticide, and harvest cost (ear mechanical harvesting or grain mechanical harvesting). The difference in other costs between the two hybrids is due to the higher harvest cost of Denghai 518 than Denghai 605.
Values are mean±SD (n=6). Different letters within a column indicate significant differences (P<0.05).

4.3. Effects of optimal nitrogen management on the profit margins of hybrids with different growth duration

Increasing the number of N application stages can significantly improve the yield and N accumulation of maize (Zhou *et al.* 2018; Du *et al.* 2019). However, with an increase in topdressing input, the realized profit may not continue to increase and may even decrease (Quan *et al.* 2021). This experimental study showed that the profit margin for the DH518 T3 treatment was lower than for the DH518 T2 treatment, while the economic benefit of the DH605 T3 treatment was significantly higher than that of the DH605 T2 treatment (Table 1). Therefore, for mid-early-maturing summer maize hybrids represented by DH518, which have high pre-anthesis N requirements but lower post-anthesis N requirements, canceling N topdressing at the VT stage and increasing the proportion of N application at the VE stage can achieve greater economic benefits. However, for late-maturing hybrids represented by DH605, which have higher post-anthesis N requirements, implementing a three-stage split application of urea is still necessary to achieve a greater profit. Grain mechanical harvesting can reduce labor input and save production costs (Yang *et al.* 2016). Compared with SAU, the application of CRU can reduce the number of stages of N application and further reduce costs (Zhang *et al.* 2022). In this experiment, due to the higher cost of CRU, the total input to the TC treatment was comparable to that of the T2 treatment, although it was still lower than that of the T3 treatment (Table 1). Considering the gross return from yield and total input, there was no difference in net income among the DH518 TC, DH518 T2, DH605 TC, and DH605 T2 treatments (Fig. 5). Understanding the N requirement characteristics of a crop to optimize the N application patterns can improve the synchronization of crop N demand and fertilizer N supply (Ye *et al.* 2013). This can augment the yield potential of hybrids with different growth durations and generate a higher profit margin (Sun *et al.* 2020; Lu *et al.* 2021). In the R6 stage, the NNI of the DH518 TC treatment approached 1, indicating an optimal N status. However, the NNI of the DH605 TC treatment was less than 1, indicating N deficiency (Appendix F). The higher pre-anthesis N uptake capacity and shorter growth duration of DH518 increased its synchronization with the CRU N supply, thereby improving the NNI of DH518 TC and DH518 T2 and ultimately achieving a profit equivalent to that of DH605 TC (Fig. 5). Therefore, the CRU-based application can completely replace the split N application of mid-early-maturing hybrids represented by DH518. Still, it cannot achieve the same economic benefits as the three-split application pattern of late-maturing hybrids represented by DH605.

4.4. Perspectives for future nitrogen management strategies

Relying solely on increasing N application to enhance yields will not only backfire, but it can also result in environmental pollution and pose a severe threat to human health (Zhang *et al.* 2021). Maximizing yields while protecting the environment by limiting the application of N fertilizers is a serious challenge for sustainable agricultural production (van Dijk *et al.* 2021). This study offers an economically feasible and significantly relevant approach. Farmers can decide, based on their specific circumstances, to adopt either N split application or co-application with CRU, with the former being more suitable for smallholders and the latter for intensive large-scale cultivation. With the continuous improvement of integrated water and fertilizer technologies and the gradual reduction of urea-coating material costs, farmers can choose between these two modes (Gao *et al.* 2015; Ren *et al.* 2023). In addition, by quantifying the relationship between the yield and N application frequency for different summer maize hybrids, this study provides an empirical basis for establishing the best N application model and improving the yield and NUE of hybrids, which can potentially have a significant impact on sustainable agricultural production.

5. Conclusion

The ^{15}N recovery rates under urea applied at the sowing stage and topdressing at the V9 stage in DH518 were higher than under topdressing at the VT stage, while the ^{15}N recovery rates from topdressing urea at the V9 stage and VT stage in DH605 were higher than those from application at the sowing stage. The pre-anthesis N uptake capacity of DH518 was higher than that of DH605. The higher pre-

anthesis N uptake capacity and the shorter growth duration of DH518 coordinated the N supply-demand balance and significantly improved the NNI. Because of the difference in N absorption capacity between the hybrids, the highest yield and economic benefit of DH605 was T3, while the highest yield and economic benefit of DH518 were associated with T2 and TC. Therefore, applying CRU as the base fertilizer or splitting the application of urea into two stages can achieve synergistic increases in both yield and net profits for mid-early-maturing hybrids compared with late-maturing hybrids, where higher yields can be obtained by applying urea in three stages.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

Data availability

The data supporting the conclusions of this article are included within the article and its additional files.

Appendices associated with this paper are available at https://doi.org/10.1016/j.jia.2024.12.028

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