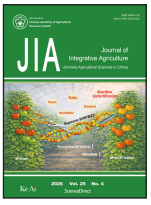
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RESEARCH ARTICLE

Dense planting and nitrogen fertilizer management improve drip-irrigated spring maize yield and nitrogen use efficiency in Northeast China

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Highlights

- The optimal nitrogen rate for maize under nitrogen fertilizer precision management (NFPM) in Northeast China is 270 kg ha^{-1}, beyond which grain yield reaches a plateau.
- NFPM synergistically improves yield-related traits and nitrogen use efficiency, outperforming CNFM and WSFM.

Abstract

Farmers in China often use nitrogen (N) fertilizers to ensure adequate crop growth. However, inappropriate applications have increased the risk of environmental pollution, lowered maize yields, and reduced profits for farmers. Proper N fertilizer management is crucial for improving yield and nitrogen use efficiency (NUE). This study conducted a three-year experiment involving nine N treatments (0, 45, 90, 135, 180, 225, 270, 315, and 360 kg ha^{-1}) on a field under nitrogen fertilizer precision management (NFPM) in Northeast China. The results were compared with studies published within the past decade that analyzed yield and dry matter (DM) content under two management practices in Northeast China: conventional nitrogen fertilization management (CNFM) and water-saving fertilization management (WSFM). The findings reveal that maize yield increases with rising N application rates up to 270 kg ha^{-1}, after which yield decreases. The kernel number (KN) and kernel weight (KW) of maize grown under NFPM were 13.7 and 14.7% higher than those grown under WSFM, respectively. Furthermore, they surpassed crops grown under CNFM by 38.4 and 21.2%, respectively. The maximum total yield of the NFPM treatment was 41.8 and 78.8% higher than under WSFM and CNFM, respectively. In addition, compared with CNFM and WSFM, NFPM significantly increased NUE across the various N-level treatments. Optimizing nitrogen management can help farmers to achieve higher yields and promote sustainable agricultural development.

Keywords: maize, yield, dense planting, drip irrigation, N use efficiency, N fertilizer management

1. Introduction

With a continuous increase in the global population, the demand for maize (*Zea mays* L.) has increased dramatically. As a staple crop in many countries, maize plays a vital role in ensuring food global security (Ranum *et al.* 2014; Li *et al.* 2017). According to the *Chinese Agricultural Development Report (2021–2030)* (Ministry of Agriculture and Rural Affairs of the People's Republic of China 2021), the total domestic maize consumption in 2020 was 296 million tons. This demand is expected to rise to 314 million tons by 2025 and 332 million tons by 2030. In 2021, the total land dedicated to maize production in China exceeded 43.35 million ha, accounting for 17.4% of the global cultivation area. However, the yield per unit area in China was only 6.3 t ha^{-1}, far less than the 11.1 t ha^{-1} achieved in the United States (FAO 2021). Amid the intensifying pressures of urbanization and

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limited arable land, increasing the crop yield per acre is vital for meeting the rising food demand and ensuring Chinese food security.

As a crucial nutrient, nitrogen (N) heavily influences maize productivity and has become a key component of modern fertilizer regimes aimed at enhancing yields (Wang *et al.* 2008; Li *et al.* 2025). N fertilizers have been used in China for less than a century but have led to a qualitative increase in crop yield, thereby supporting the rapid population growth (Tian *et al.* 2012). However, this continuous increase in N fertilizer application does lead to an exponential increase in crop yields, and it can lead to many unintended consequences (Ren *et al.* 2025). Previous reports have indicated that excessive N application causes maize to become barren during the early growth stages, increases the risk of lodging in more mature plants (Xu *et al.* 2017), exacerbates water stress, reduces the activity of biological nitrogenase in the soil, and lowers soil available N (Huang *et al.* 2023). Taken together, these findings highlight the need for appropriate management methods that achieve yield breakthroughs while reducing the negative impacts of surplus N. Recently suggested strategies for maize cultivation include using dense planting methods (Ming *et al.* 2017), implementing water-saving irrigation strategies (Abalos *et al.* 2014; Farneselli *et al.* 2015; Guardia *et al.* 2016), and dividing N fertilizer applications to better match plant life stages (Quemada *et al.* 2013; Du *et al.* 2019).

Past misconceptions have led growers to believe that more N always correlates with higher maize yields, resulting in excessive fertilization (Chen *et al.* 2015). However, previous studies have shown that this approach does not generally result in a sustained yield increase (Dai *et al.* 2015; Yang *et al.* 2017). The works of Yin *et al.* (2017) have suggested the presence of a threshold marking the rate at which additional N applications negatively impact yield. In addition to reduced yield, the excessive use of these fertilizers results in greater N losses, lower N utilization efficiency (NUE), and more N pollution (Shi *et al.* 2016; Zhu *et al.* 2016; Jiang *et al.* 2019). Previous reports have demonstrated that the agronomic efficiency (AE_N) and partial factor productivity of N (PFP_N), which are used to characterize fertilizer use efficiency (Zhu and Jin 2013), can decrease with increases in N application. Therefore, optimizing N fertilization management guides for China is necessary to improve both yield and fertilizer utilization efficiency.

At present, N fertilizer management in China encompasses conventional nitrogen fertilizer management (CNFM), water-saving fertilization management (WSFM), and nitrogen fertilizer precision management (NFPM). CNFM is the most common strategy, in which nitrogen fertilizer is applied to soil at the time of sowing (Zhao *et al.* 2013). China introduced drip irrigation technology in 1974, and by 2000, advancements had enabled its application to vital crops such as maize (Gao *et al.* 2016), facilitating the development and expansion of WSFM. Finally, NFPM has achieved promising results during nationwide pilot studies and is based on integrated irrigation fertilization through mulch drip lines (Zhang *et al.* 2020). Modern advances in fertilization were highlighted in 2020, when the Crop Physiology and Ecology Innovation Team of the Chinese Academy of Agricultural Sciences established a high-yield record of 24.9 t ha^{-1} in Chinese Spring maize using drip irrigation and fertigation in Xinjiang, China (Cheng *et al.* 2021). In Northeast China, the use of NFPM has been shown to increase maize yields by 61% compared with CNFM (Li *et al.* 2021).

The Northeast regions of China lead the country's maize production, accounting for 39% of the nation's planting area (NBS 2020). Cultivation in this region is stable, covering approximately 6×10^5 ha year-round and yielding over 40% more grain than the national average (Wang S *et al.* 2021). Farmlands in Northeast China are characterized by intensive cultivation and a high degree of mechanization. Farmers in this region tend to be highly educated and have a strong interest in contributing to the development and popularization of new management methods. The substantial production demands position Northeast China as an ideal target for efforts aimed at enhancing high-yield and high-efficiency maize production through fertilizer management. In this study, we sought to determine the optimal N rate and management practices for enhancing maize cultivation in Northeast China. We conducted a three-year field experiment and combined our results with data collected from previous maize studies to quantify the impacts of various N application rates on grain yield (GY) and NUE.

2. Materials and methods

2.1. Experimental site

A three-year (2019–2021) field trial was carried out in Qianjiadian Town, Horqin District, Tongliao City (43°37′N, 122°14′E). The test area has a temperate continental monsoon climate, with an average annual temperature of 6.1°C, an average annual rainfall of 334 mm, and sunshine hours of 3,113 h. The active accumulated temperature higher than 10°C was 3,000°C–3,200°C, and the frost-free period was 150–165 days. The meteorological parameters of the test site during the whole growth period of maize from 2019 to 2021 are shown in Fig. 1. The test site's soil type was sandy clay loam, and the soil physicochemical properties of the average (0–100 cm) soil layer before three years of sowing are shown in Table 1.

2.2. Experiment design

The trial was designed in a completely randomized block, using the maize variety Dika 159 with a planting density of 9.0×10^4 plants ha^{-1}. A N gradient was set up at every 45 kg ha^{-1} interval, resulting in nine N levels ranging from 0 to 360 kg ha^{-1}. Each N-level cell was precisely located. The experiment adopted the wide and narrow row planting mode ((80+40) cm), and the cell area was 120 m^2 (length, 10 m; width, 12 m), with three replications. Each community was equipped with a 50 L differential pressure fertilizer tank and water meter for precisely controlling the amounts of water and fertilizer.

2.3. Biomass and yield

When maize reached physiological maturity (R6), the middle six rows were selected in each cell, and the protecting rows (not less than 2 m at both ends) were removed. The area of

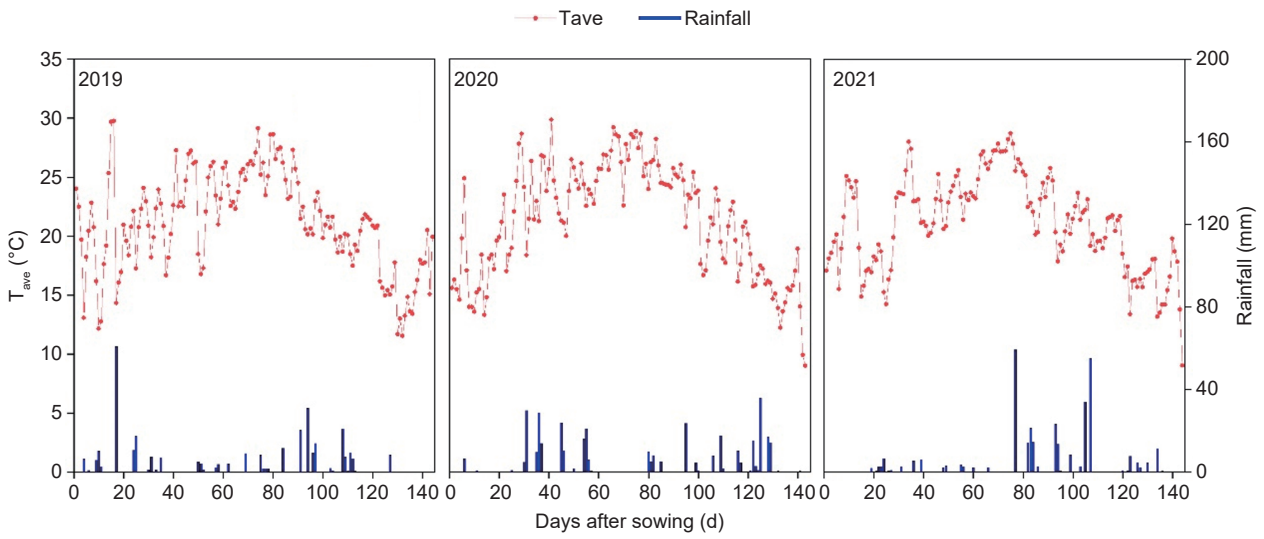


Fig. 1 Daily average temperature (T_{ave}) and rainfall during the maize growth periods in 2019–2021.

Table 1 Physicochemical properties of soil (0–100 cm) in the experimental fields

Soil depth (cm)	Organic matter (g kg^{-1})	Total nitrogen (mg g^{-1})	Alkaline-N (mg kg^{-1})	Olsen-P (mg kg^{-1})	Available K (mg kg^{-1})	pH
0–20	18.3	1.4	104.1	6.7	208.7	7.8
20–40	21.1	1.3	89.8	3.0	199.7	7.9
40–60	25.7	1.5	104.1	2.9	233.7	8.2
60–80	22.0	1.2	82.6	3.1	227.3	8.5
80–100	25.4	1.5	97.3	4.5	194.5	8.4

each sampling plot was 33 m^2 (length, 10 m; width, 3.3 m), and all the ears in each plot were harvested, counted, and weighed. The seed rate was calculated based on 20 ears that were selected as standard ear samples using the average ear weight method, and the ears were threshed and weighed. A grain moisture meter (PM-8188-A, Kett Electric Laboratory, Japan) was used to measure the moisture of the grain and the weight data were converted to 14% standard moisture. Field surveys and indoor seed examinations obtained the number of harvested ears, kernel number (KN), and kernel weight (KW). Plants from each treatment were sampled at the silking and maturity stages, and three representative plants with the same growth were selected from each treatment. Their shoots were taken, placed in a drying box at 105°C for 20 min, and baked at 85°C until the dry weight was constant. That constant weight value was used as the grain dry weight. The harvest index (HI) was calculated as follows (Liu *et al.* 2020):

$$\text{HI}=\frac{\text{Grain dry weight}}{\text{Aboveground dry matter (DM)}}$$

2.4. N use efficiency

The N partial factor productivity (PFP_N, kg kg^{-1}), and agronomic efficiency of N (AE_N, kg kg^{-1}) were calculated as follows:

$$PFP_N=Y/N_{fer}$$

$$AE_N=(Y_n-Y_0)/N_{fer}$$

where Y_n and Y_0 are the yields of different N levels (kg ha^{-1}) and the yield (kg ha^{-1}) of N_0 (Zhang *et al.* 2020), respectively.

2.5. Data collection

Published data for CNFM and WSFM in Northeast China between 2010 and 2023 were collected by using “nitrogen application rate” and “maize yield” as keywords for searching the Chinese Knowledge Resources Integrated Database (http://www.cnki.net), Web of Science (http://www.webofknowledge.com), and Science Direct (https://www.sciencedirect.com). In total, 499 data points related to yield, 442 related to KN, 490 related to KW, and 268 related to DM were collected in this literature survey. All references corresponding to the data collected in this study are available in the Appendix A. The criteria for selecting the data were as follows: (i) GY should be standardized at 14% moisture content; (ii) KN=Kernel number per ear×Harvest ears/Unit area; (iii) KW should be standardized at 14% moisture content; (iv) DM=Dry matter per plant×Harvest density; (v) HI=Grain yield per plant/DM per plant at maturity. The data for NFPM were collected from our three-year field trial.

2.6. Statistical analysis

The collected data were processed using Excel 2019 (Microsoft, Inc., Armonk, NY, USA), and then SPSS 20.0 (IBM, Inc., Armonk, NY, USA) software was used for statistical analysis. The results were analyzed using a general linear model to evaluate the effects of the factors (N, Y) and their interactions on all tested variables. The mean values of

variables were compared using the LSD-Fisher test (α=0.05).

3. Results

3.1. Relationship between yield and N application rate under NFPM

Our three-year field trial demonstrated that the N application rate greatly affects GY under N fertilizer precision management (Fig. 2). Increasing N fertilizer rates significantly enhanced production until an application rate of 270 kg ha^{-1}, at which point additional N had no significant effect on yield.

3.2. Effects of N fertilizer management on GY and DM

During our study, the N application rate significantly affected the GY and DM of maize grown under NFPM, WSFM, and CNFM (Fig. 3). In all management methods, GY and DM each exhibited an initial linear increase followed by a decrease. The relationship between GY and N application rate fits the quadratic function. According to Liu *et al.* (2023), the critical N application rate (N_{cri}, kg ha^{-1}) represents the minimum N supply required to support the maximum GY (Y_{max}, kg ha^{-1}). Based on the fitting equation, the Y_{max} of NFPM was 18.5 t ha^{-1}, representing a 41.8 and 78.8% increase compared with WSFM and CNFM, respectively. Similarly, the N_{cri} of NFPM was 500 kg ha^{-1}, which was 80 and 125% higher than WSFM and CNFM, respectively. In addition, the maximum DM (DM_{max}) of NFPM was 34.73 t ha^{-1}, or 42.9 and 63.5% higher than WSFM and CNFM, respectively. Finally, the N_{cri} of NFPM was 666.7 kg ha^{-1}, or 122 and 140% greater than WSFM and CNFM, respectively.

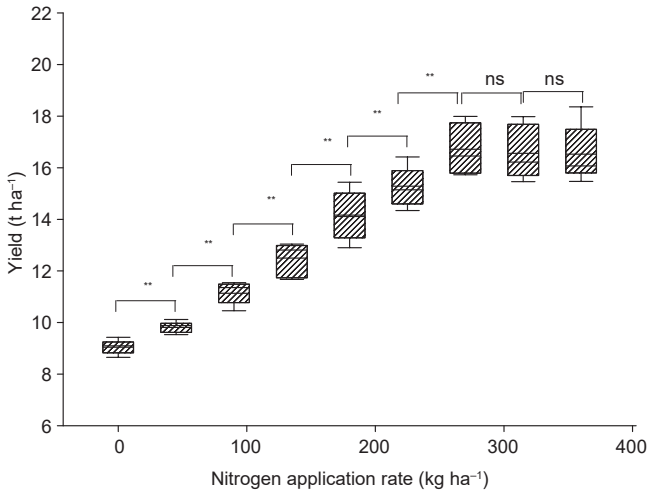


Fig. 2 Relationship between nitrogen application rate and maize yield in nitrogen fertilizer precision management (NFPM). ns, not significant; **, significant at *P*<0.01.

3.3. Effects of N fertilizer management on KN and KW

N fertilizer application significantly impacted KN and KW under all three tested management methods, mirroring the relationship between N fertilizer and yield. According to the fitting equation, the maximum KN (KN_{max}) of NFPM was 4,915 kernels m^{-2}, representing an increase of 13.8 and 38.4% compared with WSFM and CNFM, respectively. The critical N supply (N_{cri}, kg ha^{-1}) of NFPM was 450 kg ha^{-1}, or respective increases of 73 and 100% compared with WSFM and CNFM. The maximum KW (KW_{max}) of NFPM was 406.4 g, which was 14.7 and 21.1% higher than WSFM and CNFM, respectively. Finally, the critical N supply of NFPM was 500 kg ha^{-1}, an increase of 100 and 122% compared with WSFM and CNFM, respectively.

3.4. Effects of N fertilizer management on HI

In this study, N application rate had no significant effect on the HI of NFPM or WSFM (Fig. 4). The HI values remained

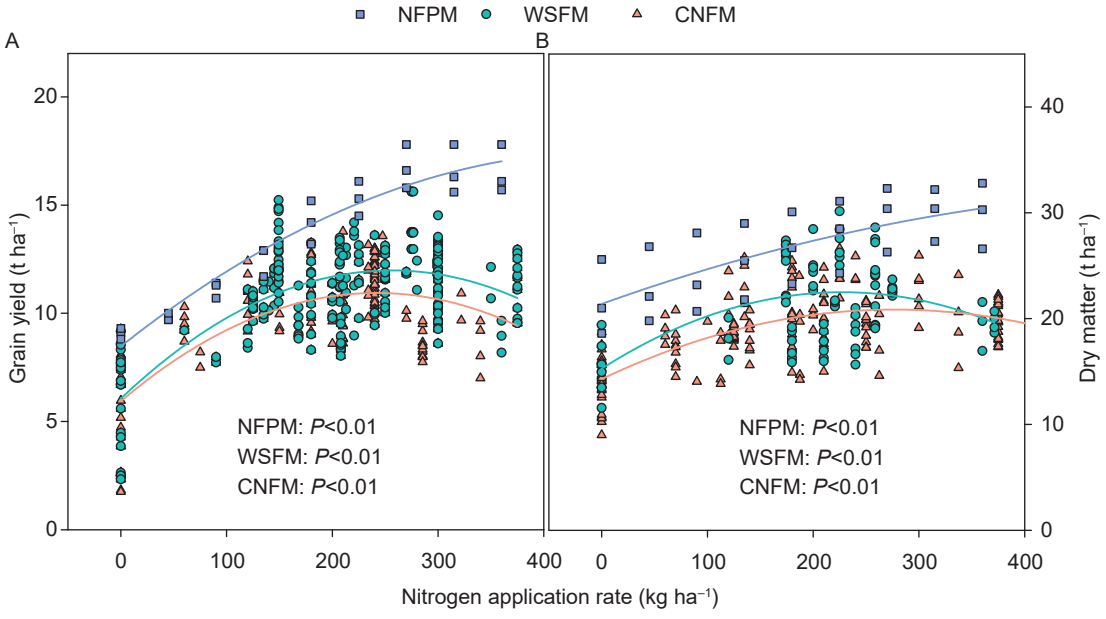


Fig. 3 Grain yield and dry matter in response to three N fertilizer management approaches. NFPM, nitrogen fertilizer precision management; WSFM, water-saving fertilization management across various N application rates; CNFM, conventional nitrogen fertilization management.

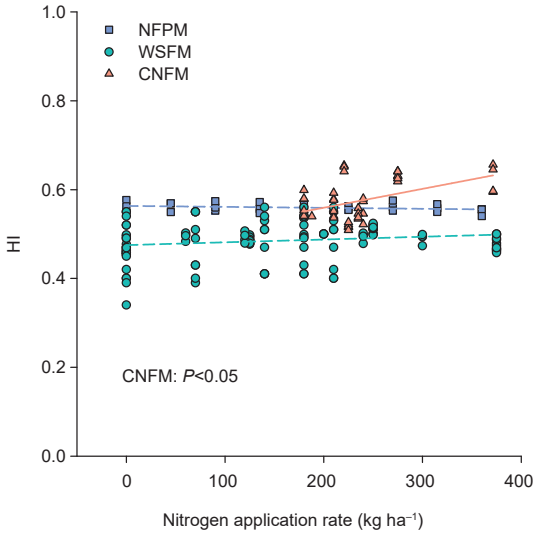


Fig. 4 Harvest index (HI) in response to three nitrogen fertilizer management approaches across various N application rates. NFPM, nitrogen fertilizer precision management; WSFM, water-saving fertilization management across various N application rates; CNFM, conventional nitrogen fertilization management.

between 0.4 and 0.6, and the HI of NFPM was significantly higher than WSFM. N application had a significant promotional effect on the HI of maize. These results indicate that changing the N management strategy could reduce the effect of N application rate on the HI of maize populations with different densities, and dense planting can increase the HI of maize.

3.5. Effects of N fertilizer management on NUE

A linear regression model was established through the regression analysis of NUE in the three different nitrogen management modes. The results show that the rate of nitrogen application had a significant impact on NUE across all N management strategies. In comparing the regression models of WSFM and CNFM, the two models are highly consistent, leading to the shared regression model depicted in Fig. 5. PFP_N decreased with a rise in the N application rate, which fit the exponential decay function. Furthermore, the relative rate of increase rose in tandem with the N application rate. AE_N demonstrated an initial linear increase before decreasing, a relationship that fit the quadratic function. According to the fitting equation, the maximum AE_N observed in this study was 31.6 kg kg^{-1}, an increase of 25.3% compared with rates observed in the previous studies analyzed for this experiment. In addition, the critical N supply of this study was 257 kg ha^{-1}, which was 131.5% higher than reported in other studies.

4. Discussion

4.1. Effect of N fertilizer management on maximum yield and the critical N application rate

N is the most influential elemental nutrient affecting grain yield. Modern agriculture has increasingly relied on N fertilizers to raise yields (Wang *et al.* 2008). However, the optimal application rate of N fertilizer is affected by many factors, such as soil fertility, tillage practices, and planting density (Du *et al.* 2017; Li *et al.* 2018). While supplemental N is correlated with strong plant growth, previous studies have indicated that exceeding a certain application rate fails to produce additional yield (Huang *et al.* 2007). Our field trials revealed that increasing N fertilizer rates up to 270 kg ha^{-1} results in higher yields. However, beyond the rate of 270 kg ha^{-1}, additional N no longer positively affects yield (Fig. 2). These findings are consistent with the results of Zhai *et al.* (2022), who reported that dense maize plantings in Northwest China managed with water and fertilizer integrated fractional

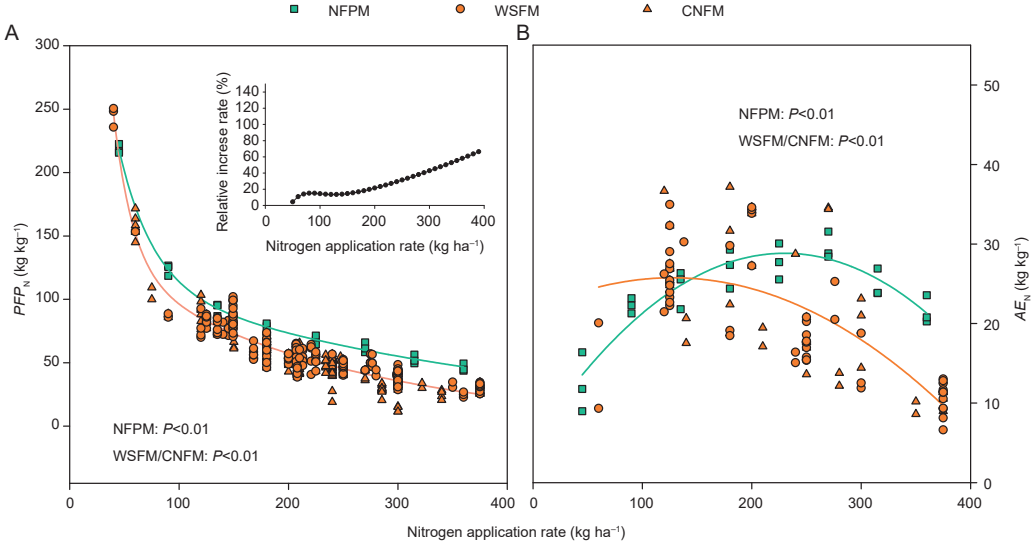


Fig. 5 Partial factor productivity of N (PFP_N) and agronomic efficiency of N (AE_N) of three N fertilizer management methods in response to N application rate. NFPM, nitrogen fertilizer precision management; WSFM, water-saving fertilization management across various N application rates; CNFM, conventional nitrogen fertilization management.

fertilization showed increasing yields with rising N application rates up to 360 kg ha^{-1}, beyond which additional N had no significant effect on the yield. In our study, both the N_{cri} and Y_{max} of NFPM were significantly higher than those of the other two N fertilizer management methods (Fig. 3-A). Collectively, these results indicate the presence of an N application threshold, beyond which yield no longer increases. Furthermore, the optimization of N fertilizer management allows the maize to effectively utilize supplementary N, thus raising the application threshold and achieving yield breakthroughs. A previous study by Thorburn *et al.* (2024) reported that raising the N application rate threshold could improve Y_{max}, but it was not the decisive factor.

In our study, KN and KW increased with an increasing N application rate (Fig. 6), suggesting that they are the primary factors contributing to the observed increase in growth, consistent with previous studies (Wang *et al.* 2023; Bao *et al.* 2025). Implementing optimized planting density along with drip irrigation has been demonstrated to improve kernel number and kernel weight (Yan *et al.* 2026). DM serves as the foundation for grain formation, with increases in DM accumulation and its transfer to grain directly influencing crop yield within a certain range (Ma *et al.* 2017; Xue *et al.* 2020; Liu *et al.* 2022). Liu *et al.* (2023) highlighted that dry matter accumulation, particularly during the post-anthesis stage, is a critical factor for enhancing crop yield. In this study, the DM_{max} and N_{cri} of NFPM were higher than the other two N fertilizer management methods (Fig. 3-B), indicating that optimizing the N application could increase yield by influencing DM accumulation.

4.2. Optimizing N fertilizer management to achieve high NUE

Optimizing N management is generally accepted to be the most effective way to increase N use efficiency without sacrificing crop yield (Yong *et al.* 2018; Duan *et al.* 2019). The excessive use of N fertilizer results in larger N losses and reduced utilization efficiency, which is typically measured in terms of AE_N and PFP_N (Zhu and Jin 2013). Our findings are consistent with previous reports which indicated that NUE, PFP_N, and AE_N decrease with increasing N applications (Jiang *et al.* 2019; Huang *et al.* 2023). Our results show that the method of N fertilizer management significantly influences PFP_N and AE_N. The PFP_N of NFPM was significantly higher than those of the other two methods, particularly with increases in the N application rate (Fig. 4-A). Simultaneously, the maximum value of AE_N in NFPM was realized under the highest N treatment, indicating that the NUE can be optimized through management method (Fig. 4-B). In general, higher N application rates will increase N loss and crop yield while reducing AE_N. Therefore, when the N application exceeds the optimal threshold, the yield can no longer be increased through additional inputs (Du *et al.* 2024). In this study, we determined that optimizing N fertilizer management could increase the AE_N, N_{cri}, and yield. These results differ from previous studies which reported that increases in N could not further increase the yield (Huang *et al.* 2023). Overall, our work indicates that the yield-increasing potential of N fertilizer can be increased with minimal harm to the environment through management efforts.

4.3. Greater planting density can improve N utilization capacity

In recent years, researchers have found that dense plantings allow growers around the globe to obtain high maize yields. However, the optimal density is affected by factors such as resources, environmental conditions, variety, and cultivation measures (Li *et al.* 2015; Ming *et al.* 2017). Our research used a density of roughly 90,000 plants ha^{-1} under NFPM, while WSPM and CNFM averaged approximately 60,000

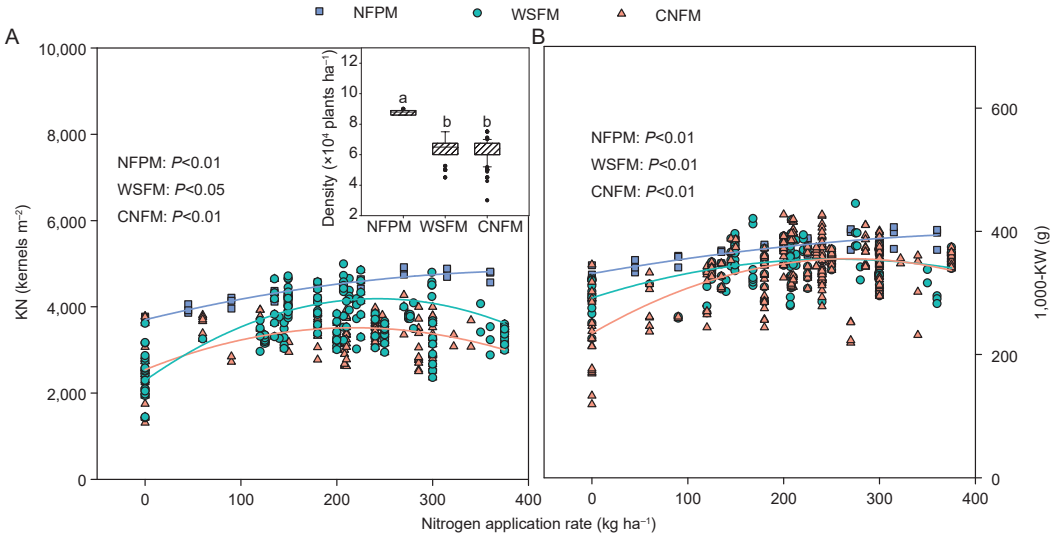


Fig. 6 Kernel number (KN) and 1,000-kernel weight (KW) in response to three N fertilizer management approaches across various N application rates. NFPM, nitrogen fertilizer precision management; WSFM, water-saving fertilization management across various N application rates; CNFM, conventional nitrogen fertilization management. Different lowercase letters indicate significant differences at the P<0.05 level.

plants ha^{-1} (Fig. 6). The Y_{max} of NFPM rose by 41.8 and 78.8% in comparison with WSFM and CNFM, respectively (Fig. 3-A), while the maximum AE_N of NFPM increased by an average of 25.3% (Fig. 5-B). These results show that a higher planting density can improve yield and NUE, supporting previous research (Wei *et al.* 2024; Guo *et al.* 2025). In addition, we found that planting density and N application interact to produce high yields and efficient N use. Dense plantings allow maize to better utilize soil nutrients, resulting in better yields (Shi *et al*. 2016). Moreover, increasing the planting density can optimize the structure and morphology of underground roots, promote the development of bacterial communities, and improve the ability of maize to absorb and utilize N in the soil (Zhang *et al.* 2023). However, Hou *et al.* (2023) indicated that dense maize plantings display significantly increased soil microbial biomasses, which play a key role in soil–root interactions (Xiao *et al*. 2019; Gu *et al.* 2025). This relationship affects soil nutrient availability and soil fertility (Hu *et al.* 2017; Bai *et al.* 2020; Beltran-Garcia *et al.* 2021), in turn affecting nutrient uptake. This study showed that optimized N management strategies can improve the GY and NUE.

5. Conclusion

Optimizing N fertilizer management and identifying the rate threshold are crucial for synergistically achieving high GY and NUE. Our results demonstrate that N application rates of approximately 270 kg ha^{-1} contribute to the realization of both goals. Furthermore, we determined that compared to CNFM and WSFM, the use of NFPM in maize cultivation improves DM accumulation, increases KN, KW, GY, and NUE, and makes full use of supplementary N. These findings provide a basis for the improvement and sustainable development of maize production in Northeast China.

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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.

Appendix associated with this paper is available at https://doi.org/10.1016/j.jia.2024.09.032

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