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Optimizing Maize Yield and Resource Efficiency Using Surface Drip Fertilization in Huang-Huai-Hai: Impact of Increased Planting Density and Reduced Nitrogen Application Rate

Liqian Wu [1,2,†], Guoqiang Zhang [1,2,†], Zhenhua Yan [1,2], Shang Gao [1,2], Honggen Xu [1,2], Jiaqiang Zhou [1,2], Dianjun Li [1,2], Yi Liu [1,2], Ruizhi Xie [1,2], Bo Ming [1,2], Jun Xue [1,2], Peng Hou [1,2], Shaokun Li [1,2] and Keru Wang [1,2,*]

1 State Key Laboratory of Crop Gene Resources and Breeding, Institute of Crop Sciences, Chinese Academy of Agricultural Sciences, Beijing 100081, China; 82101212198@caas.cn (L.W.); zhangguoqiang@caas.cn (G.Z.); yanzhenhua1996@163.com (Z.Y.); g382824817@126.com (S.G.); xuhonggen2017@163.com (H.X.); zhoujq210@163.com (J.Z.); 18956161499@163.com (D.L.); wowlly@126.com (Y.L.); xieruizhi@caas.cn (R.X.); mingbo@caas.cn (B.M.); xuejun@caas.cn (J.X.); houpeng@caas.cn (P.H.); lishaokun@caas.cn (S.L.)
2 Zhongyuan Research Center, Chinese Academy of Agricultural Sciences, Xinxiang 453500, China
* Correspondence: wangkeru@caas.cn
† These authors contributed equally to this work.

Abstract: Improving crop yield and resource utilization efficiency is essential for agricultural productivity. In the Huang-Huai-Hai maize region of China, optimizing planting density, nitrogen (N) application, and fertilization methods are key strategies for enhancing maize yield and N use efficiency. However, traditional approaches have often hindered these improvements. To address this issue, we conducted a study in Baoding, Hebei, from 2022 to 2023, focusing on planting density, the N application rate, and the fertilization method on grain yield, N use efficiency, water use efficiency (WUE), and economic benefits. The trial involved two planting densities: 6.0×10^4 plants ha^{-1} (D1, typical local density) and 9.0×10^4 plants ha^{-1} (D2). Five N application rates were tested: 0 (N0), 120 kg ha^{-1} (N1), 180 kg ha^{-1} (N2), 240 kg ha^{-1} (N3), and 300 kg ha^{-1} (N4). The control treatment (D1N4) utilized the local planting density and traditional fertilization methods. Our findings revealed a positive correlation between the maize yield and N application rate, with the maximum yields (13.78–13.88 t ha^{-1}), high WUE (24.42–29.85 kg m^{-3}), agronomic efficiency of N (AE_N) (18.11–19.00 kg kg^{-1}), and economic benefits (2.44×10^4–2.47×10^4 CNY ha^{-1}) observed with D2N3 and surface drip fertilization. This was significantly higher than the yield and resource efficiency of traditional fertilization methods and saved fertilizer and production costs. Therefore, adopting surface drip fertilization, adjusting planting density, and optimizing N application rates proved effective in enhancing maize yield and resource utilization efficiency in the Huang-Huai-Hai maize region.

Keywords: surface drip fertilization; planting density; N application rate; yield; water and nitrogen use efficiency

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1. Introduction

Maize holds a significant position in Chinese agriculture, boasting the largest cultivation area and overall production. However, its yield per unit area remains relatively low [1]. The Huang-Huai-Hai region, a major summer maize hub, faces challenges from high temperatures and drought, impacting maize growth and development [2]. With an average planting density of 6.3×10^4 plants ha^{-1} [3] in this region, low density often translates to suboptimal yield levels, exacerbated by the prevalent "single basal fertilization" approach. Farmers frequently resort to excessive nitrogen fertilization in pursuit of higher maize yields, leading to increased yield without commensurate income gains, significant N fertilizer wastage, and diminished nitrogen utilization efficiency. Excessive nitrogen also contributes to reduced nitrogen utilization efficiency, resource wastage, and environmental pollution [4,5], highlighting the need to balance yield enhancement with environmental sustainability [6].

Research has elucidated various nitrogen application models, ranging from "quadratic curve" [7] and "linear + plateau" [8] to "quadratic + plateau" [9]. Insufficient nitrogen application can prematurely age lower maize leaves, hamper photosynthetic capacity, reduce dry matter accumulation, and impair grain formation and weight. Conversely, excessive nitrogen fosters early-stage overgrowth, elevates lodging risks, and diminishes nitrogen use efficiency, ultimately impacting yield [10].

Research exemplified by studies such as that of Sui et al. [11] elucidated that within a certain range, increasing nitrogen application rates significantly augmented total nitrogen accumulation in maize. However, this came at the cost of reduced nitrogen partial factor productivity and agronomic efficiency, leading to a plateau in yield per unit area despite nitrogen increments. Similarly, Xu et al. [12] demonstrated that under conventional fertilization, maize yield at a nitrogen application rate of 180 kg ha^{-1} was only 11.3 t ha^{-1}, not significantly different from that at 360 kg ha^{-1}, indicating a saturation point where further nitrogen application fails to enhance yield. Consequently, optimizing nitrogen fertilizer production efficiency entails reducing nitrogen application while maintaining existing fertilization methods.

Furthermore, research suggests that aligning nitrogen application with crop demand and reallocating nitrogen fertilizer to the middle–late stages can simultaneously bolster yield and nitrogen use efficiency while mitigating environmental risks [13,14]. Moreover, reasonable increases in planting density have been proposed to enhance maize yield and nitrogen fertilizer utilization efficiency effectively [15,16]. In irrigated maize regions like the Huang-Huai-Hai area, optimizing fertilization frequency and staged fertilizer application under integrated water and fertilizer conditions has demonstrated further improvements in maize yield and nitrogen fertilizer utilization efficiency [17,18]. Innovations in fertilization techniques in irrigated agricultural areas play a pivotal role in enhancing crop yield and optimizing resource efficiency. Therefore, adopting integrated drip irrigation systems that combine water and fertilizer may represent a promising avenue for further enhancing maize yield and optimizing water and fertilizer efficiency in the Huang-Huai-Hai maize belt.

Surface drip fertilization represents an innovative agricultural practice that seamlessly integrates fertilization with surface drip irrigation technology. This approach tailors nitrogen fertilizer application to match the specific fertilizer demands of each maize growth stage. By precisely delivering water and fertilizer directly to the root zone, it facilitates efficient water–fertilizer coupling, enables the accurate control of water and fertilizer distribution, and mitigates nitrogen volatilization, loss, and leaching [19]. Research indicates that surface drip irrigation, when compared to conventional methods, can lead to substantial water savings of around 50%, reduce fertilizer usage by 40–50%, and enhance yields by 20–40%. These benefits have been observed in both the northwest irrigated maize area and the northeast spring maize area, achieved through the implementation of film surface drip irrigation and subsurface drip irrigation, coupled with 6–8 applications of nitrogen fertilizer post-seeding [20,21]. In northwest India, fertigation at a 10-day interval with seven splits in maize under a drip irrigation system increased the yield, water productivity, and N recovery efficiency by 13.7%, 259%, and 29% compared to furrow irrigation, respectively [22]. A study in the United States showed that compared with single fertilization by surface furrow irrigation, the yield of maize increased by 17.84% by subsurface drip irrigation [23]. Furthermore, studies conducted by Deng et al. [24] demonstrated that adjusting nitrogen application rates at different growth stages can significantly impact grain yield. Specifically, split applying 180 kg ha^{-1} of nitrogen fertilizer resulted in comparable grain yields to single applications of 240 kg ha^{-1}, with the additional advantage of yielding 6.7–11.5% higher yields than single applications of 180 kg ha^{-1}. Therefore, surface drip fertilization not only ensures grain yield stability but also reduces nitrogen application rates while enhancing nitrogen use efficiency.

A strategic increase in planting density stands out as a primary avenue for augmenting maize yield. Research indicates that elevating the density of summer maize to 9.0×10^4 plants ha^{-1} yields a significant increase in maize production [25]. Enhancing planting density, coupled with integrated water and fertilizer nitrogen application, and optimizing nitrogen application practices are pivotal agronomic strategies for amplifying maize grain yield and nitrogen production efficiency. However, prior studies predominantly concentrated on assessing the impact of varying nitrogen application rates on summer maize yield and the efficiency of water and fertilizer utilization in the Huang-Huai-Hai region, under a planting density of approximately 6.3×10^4 plants ha^{-1} and conventional fertilization methods. Yet, there remains a paucity of research examining the effects of diverse nitrogen application rates on maize yield and water and fertilizer use efficiency under conditions of surface drip fertilization and high plant populations.

Therefore, this study aims to achieve two primary objectives: (1) elucidate the influence of different fertilization methods, densities, and nitrogen application rates on the yield, water productivity, nitrogen use efficiency, and economic benefits of summer maize and (2) determine the optimal fertilizer regimen under surface drip fertilization for varying maize populations. These findings hold the potential to furnish a theoretical framework and technical guidance for enhancing yield, curbing nitrogen usage, and ensuring food security in summer maize cultivation across the northern Huang-Huai-Hai region.

2. Materials and Methods

2.1. Experimental Site

The research was conducted at Shuofeng Farm, Gaoyang County (38°56′ N, 115°94′ E), Hebei Province, China, spanning from 2022 to 2023. The total rainfall recorded during the maize growth period over the two-year study period was 373.6 mm and 530.2 mm, respectively. Figure 1 illustrates the rainfall and average temperatures observed during the maize growth phase. The soil at the experimental site, spanning 0–60 cm, exhibited a bulk density of 1.40 g cm^{-3} with a pH level of 8.0. Additionally, the soil contained 17.7 g kg^{-1} of organic matter, 1.07 g kg^{-1} of total nitrogen, 106 mg kg^{-1} of alkali-hydrolytic nitrogen, 40.7 mg kg^{-1} of available phosphorus, and 154 mg kg^{-1} of available potassium.

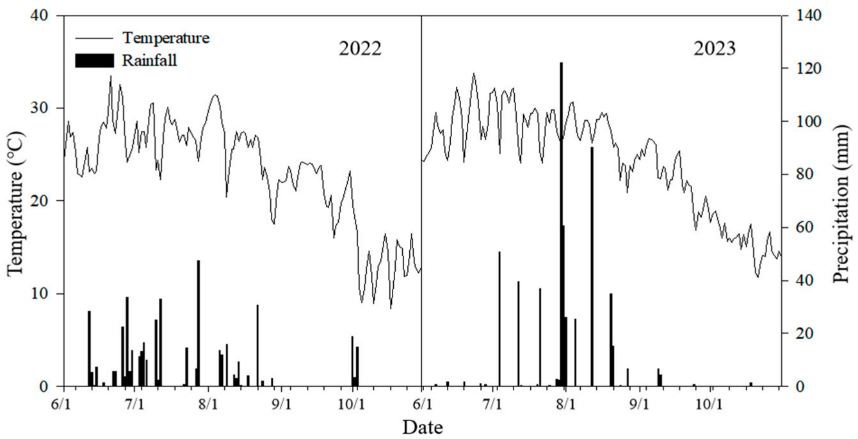

Figure 1. Meteorological data of the summer maize growth period from 2022 to 2023.

2.2. Experimental Design

The experiment employed a split-plot design, with variety as the main plot, density as the split-plot, and nitrogen application as the re-split-plot. In both 2022 and 2023, the Jingnongke 728 (JNK728) maize variety was planted at two densities of 6.0×10^4 plants ha^{-1} (D1, the planting density of local farmers) and 9.0×10^4 pants ha^{-1} (D2). Five N application rates were used: 0 (N0), 120 kg ha^{-1} (N1), 180 kg ha^{-1} (N2), 240 kg ha^{-1} (N3), and

300 kg ha^{-1} (N4, representing the local farmer's N application rate, CK). Each treatment was replicated three times, with each plot measuring 72 m^2.

The planting configuration adopted a row spacing of 60 cm. In 2022, sowing took place on June 28, with maturity occurring on October 16. In 2023, sowing occurred on June 23, with maturity on October 11. The fore crops for two years were all wheat. When sowing, 90 kg ha^{-1} N was applied, and surface drip irrigation was used for topdressing at jointing and booting stages, with a total nitrogen application rate of 210 kg ha^{-1} and an irrigation amount of 225 mm. The control treatment followed traditional fertilization methods, applying 300 kg ha^{-1} N, 108 kg ha^{-1} P_2O_5, and 180 kg ha^{-1} K_2O during seeding, followed by 225 mm of water coverage with flood irrigation after seeding every year. Other treatments utilized surface drip fertilization. Each row was equipped with a drip irrigation belt placed 20 cm away from the plants. For the N0 treatment, no N was applied, but 108 kg P ha^{-1} (triple superphosphate, P_2O_5 46%) and 180 kg K ha^{-1} (potassium sulfate, K_2O 50%) were applied as seed fertilizers over two years. For the other N treatments, 45 kg ha^{-1} N (urea, N 46%), 108 kg ha^{-1} P_2O_5, and 30 kg ha^{-1} K_2O were applied as seed fertilizers before sowing. Following seeding, 35 mm of drip water was used to facilitate seed germination. The remaining N and K_2O were applied with water in equal proportions at the 9th spreading leaf (V9, 35 days from sowing), 12th spreading leaf (V12, 42 days from sowing), silking stage (R1, 52 days from sowing), and 15 days after silking (R1 + 15 d, 69 days from sowing), with each irrigation amounting to 30 mm each time. The specific nitrogen application rates are detailed in Table 1. Figure 2 is a scene of surface drip fertilization in the field. Chemical control measures included applying 300 mL ha^{-1} of "amine-ethethylene" at the 6th to 8th leaves and the strict management of field diseases, pests, and weeds.

Table 1. N application rate of maize under different treatments at different growth stages.

Treatment	Sowing Date	V9	V12	R1	R1 + 15 d	Total (kg ha^{-1})
CK	300	0	0	0	0	300
N0	0	0	0	0	0	0
N1	45	18.75	18.75	18.75	18.75	120
N2	45	33.75	33.75	33.75	33.75	180
N3	45	48.75	48.75	48.75	48.75	240
N4	45	63.75	63.75	63.75	63.75	300

Note: V9: 9th spreading leaf, V12: 12th spreading leaf, R1: silking date, R1 + 15 d: 15 days after silking. CK: traditional planting method, 300 kg ha^{-1}; N0: no nitrogen application; N1: 120 kg ha^{-1}; N2: 180 kg ha^{-1}; N3: 240 kg ha^{-1}; N4: 300 kg ha^{-1}.

Figure 2. Scene of surface drip fertilization.

2.3. Sampling and Measurement

During the silking stage (R1) and at maturity (R6), five plants displaying uniform growth were chosen from each treatment. These plants were then separated into stems, leaves, tassels, husks, cobs, and kernels. Subsequently, they were subjected to immobilization at 105 °C for 30 min, followed by drying to a constant weight at 80 °C, which was the dry matter accumulation (DM) of each organ. Dry matter accumulation post-anthesis (DMA, t ha^{-1}) and the harvest index (HI) were calculated using the following Equations (1) and (2):

$$\text{DMA} = \text{DM at R6} - \text{DM at R1} \tag{1}$$

$$\text{HI} = \text{DM of grain}/\text{DM of plant} \tag{2}$$

Before sowing and after harvesting, the soil mass water content was measured in 100 cm soil samples at 20 cm intervals. The soil water storage (mm) was calculated as the product of the soil mass water content (%), soil bulk density (g cm^{-3}), soil depth (cm), and a constant factor of 10 [26]. Given that the groundwater depth in the test site area is below 40 m, groundwater recharge was considered negligible. Additionally, deep seepage was disregarded since the infiltration depth of precipitation does not exceed 1 m. The water required for crop growth primarily consisted of irrigation water and rainfall. Evapotranspiration (ET, mm), water use efficiency (WUE, kg m^{-3}), and irrigation water use efficiency (IWUE, kg m^{-3}) were calculated using the following Equations (3)–(5) [27]:

$$\text{ET} = \text{I} + \text{P} - (\text{W}_1 - \text{W}_2) \tag{3}$$

$$\text{WUE} = \text{Y}/\text{ET} \tag{4}$$

$$\text{IWUE} = \text{Y}/\text{I} \tag{5}$$

where I (mm) represents the irrigation amount during the growth period, P (mm) is the precipitation during the growth period, and W_1 (mm) and W_2 (mm) represent 0–100 cm soil water storage at sowing and harvesting, respectively. Y (kg ha^{-1}) is the grain yield for each treatment.

At maturity, parameters including ear number, grain number per ear, and 100-grain weight were recorded. The grain moisture content was measured using a PM-8188 device certified and calibrated by the state. The actual yield was determined based on the national grain moisture standard of 14%. The nitrogen partial factor productivity (PFP_N, kg kg^{-1}) and nitrogen agronomic efficiency (AE_N, kg kg^{-1}) were computed using the following Equations (6) and (7) [22,28]:

$$\text{PFP}_\text{N} = \text{Y}_\text{N}/\text{N} \tag{6}$$

$$\text{AE}_\text{N} = (\text{Y}_\text{N} - \text{Y}_0)/\text{N} \tag{7}$$

where Y_N (kg ha^{-1}) and Y_0 (kg ha^{-1}) represent the grain yield in N application treatments and N0 treatments, respectively, and N (kg ha^{-1}) is the N application rate.

The economic benefit and output/input were determined based on the grain output value and production input. Equations (8)–(11) were employed to compute the economic benefit (CNY ha^{-1}), output/input, grain output value (CNY ha^{-1}), and production input (CNY ha^{-1}) [29]:

$$\text{Economic benefit} = \text{grain output value} - \text{production input} \tag{8}$$

$$\text{Output/Input} = \text{economic benefit}/\text{production input} \tag{9}$$

$$\text{Grain output value} = \text{Y} \times \text{maize unit price (2.4 CNY kg}^{-1}) \tag{10}$$

$$\text{Production input} = \text{seed cost} + \text{fertilizer cost} + \text{irrigation cost} + \text{pipeline and labor cost} + \text{others} \tag{11}$$

2.4. Statistical Analysis

Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA, USA) and SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA) were employed for data analysis and plot preparation, respectively. An analysis of variance (ANOVA) was conducted to assess differences in dry matter, yield, ET, WUE, IWUE, PFP_N, and AE_N. The general linear model program of SPSS 17.0 (SPSS Inc., Chicago, IL, USA) was utilized for performing the ANOVA. The least significant difference (LSD) at the 0.05 level was applied to compare mean values between treatments.

3. Results

3.1. Dry Matter Accumulation (DM) and Harvest Index (HI)

Significant differences were observed in the DM and HI among different treatments, exhibiting a consistent pattern (Table 2). Increasing the planting density from D1 to D2 resulted in a respective increase in the DM at R1, DM at R6, DMA, and HI by 22.24%, 33.79%, 41.39%, and 9.12%, respectively. Within the same density, elevating the N application rate initially led to an increase in the DM at R1, DM at R6, DMA, and HI, followed by a plateau phase where further increments were not significant. The peak values for D1 and D2 were observed at N2 and N3, respectively. Compared to CK, D1N2 exhibited enhancements of 7.21%, 12.60%, 16.74%, and 7.62% in the DM at R1, DM at R6, DMA, and HI, respectively, while D2N3 showed improvements of 36.41%, 55.24%, 40.54%, and 69.52% higher than CK in the same parameters.

Table 2. The effects of different treatments on the dry matter accumulation and HI of maize.

Year	Density	Treatment	DM at R1 ($t\ ha^{-1}$)	DM at R6 ($t\ ha^{-1}$)	DMA ($t\ ha^{-1}$)	HI
2022	D1	CK	6.23 c	14.25 c	8.02 b	0.47 b
		N0	4.55 d	10.56 d	6.01 d	0.43 c
		N1	5.40 b	12.93 b	7.54 c	0.47 b
		N2	6.61 a	16.29 a	9.68 a	0.51 a
		N3	6.77 a	16.33 a	9.56 a	0.52 a
		N4	6.82 a	16.32 a	9.50 a	0.53 a
	D2	N0	6.44 c	15.54 d	9.11 d	0.48 c
		N1	6.91 b	17.21 c	10.30 c	0.51 bc
		N2	7.30 b	18.87 b	11.57 b	0.55 ab
		N3	8.49 a	22.43 a	13.94 a	0.59 a
		N4	8.42 a	22.37 a	13.95 a	0.57 a
2023	D1	CK	6.31 b	14.90 b	8.59 b	0.50 bc
		N0	4.66 c	10.61 c	5.95 d	0.46 d
		N1	5.67 b	13.07 b	7.39 c	0.49 cd
		N2	6.84 ab	16.52 a	9.68 a	0.53 ab
		N3	6.99 a	16.70 a	9.71 a	0.54 a
		N4	6.75 ab	16.61 a	9.85 a	0.54 a
	D2	N0	6.26 d	15.30 d	9.04 d	0.50 c
		N1	6.71 c	17.57 c	10.86 c	0.53 bc
		N2	7.34 b	19.34 b	12.00 b	0.56 ab
		N3	8.61 a	22.80 a	14.19 a	0.60 a
		N4	8.77 a	23.82 a	15.06 a	0.59 a

Note: DM: dry matter accumulation; DMA: dry matter accumulation post-anthesis; HI: harvest index. R1: silking date; R6: maturity date. D1: 6.0×10^4 plants ha^{-1}; D2: 9.0×10^4 plants ha^{-1}. CK: traditional planting method, 300 kg ha^{-1}; N0: no nitrogen application; N1: 120 kg ha^{-1}; N2: 180 kg ha^{-1}; N3: 240 kg ha^{-1}; N4: 300 kg ha^{-1}. Different letters in the same column indicate significant differences between different treatments ($p < 0.05$).

3.2. Yield and Yield Components

Grain yield and its components were significantly influenced by plant density, the N application rate, and their interaction (Tables 3 and 4). At identical N application rates, elevating planting density significantly increased the ear number while decreasing the grain number per ear and 100-grain weight by 19.42% and 7.62%, respectively, leading to a 21.17% increase in yield. Within the same density, increasing N application initially raised the grain number per ear, 100-grain weight, and yield, eventually stabilizing. Surface drip fertilization resulted in a significantly higher grain number per ear, 100-grain weight, and yield compared to CK. At D1 density, the yield plateaued after reaching a N application rate of 180 kg ha^{-1}, with D1N2 exhibiting notable enhancements of 14.11%, 12.81%, and 14.99% in the grain number per ear, 100-grain weight, and yield, respectively, compared to CK. Similarly, at D2 density, the yield plateaued after a N application rate of 240 kg ha^{-1}, with D2N3 showing a decrease of 2.62% in the grain number per ear but increases of 7.78% and 48.49% in the 100-grain weight and yield, respectively, compared to CK.

Table 3. The effects of different treatments on the grain yield and yield components of maize.

Year	Density	Treatment	Ear Number ($\times 10^4$ Ear ha^{-1})	Grain Number per Ear	100-Grain Weight (g)	Yield (t ha^{-1})
2022	D1	CK	5.56 a	413 b	29.31 b	9.38 b
		N0	5.54 a	379 c	27.07 c	7.91 c
		N1	5.67 a	396 b	30.86 b	9.68 b
		N2	5.67 a	471 a	33.25 a	10.74 a
		N3	5.69 a	473 a	33.39 a	10.68 a
		N4	5.88 a	476 a	34.18 a	10.67 a
	D2	N0	8.11 a	285 d	24.41 d	9.22 d
		N1	8.28 a	313 c	27.49 c	11.10 c
		N2	8.11 a	377 b	28.15 bc	12.39 b
		N3	8.44 a	411 a	29.32 ab	13.78 a
		N4	8.44 a	421 a	30.09 a	13.40 a
2023	D1	CK	5.89 a	432 b	30.70 b	9.25 b
		N0	5.33 a	373 c	26.79 c	8.06 c
		N1	5.78 a	425 b	30.73 b	9.57 b
		N2	6.00 a	487 a	34.08 a	10.68 a
		N3	5.06 a	494 a	35.18 a	10.86 a
		N4	5.61 a	492 a	34.43 a	11.09 a
	D2	N0	8.35 a	283 e	27.69 d	9.53 d
		N1	8.44 a	344 d	28.99 c	11.30 c
		N2	8.78 a	367 c	30.93 b	12.47 b
		N3	8.83 a	411 a	34.32 a	13.88 a
		N4	8.39 a	384 b	33.24 a	14.03 a

Note: D1: 6.0 × 10^4 plants ha^{-1}; D2: 9.0 × 10^4 plants ha^{-1}. CK: traditional planting method, 300 kg ha^{-1}; N0: no nitrogen application; N1: 120 kg ha^{-1}; N2: 180 kg ha^{-1}; N3: 240 kg ha^{-1}; N4: 300 kg ha^{-1}. Different letters in the same column indicate significant differences between different treatments ($p < 0.05$).

Table 4. Analysis of variance of year, fertilization method, density, and N application rate on yield and yield components.

Variation Source	Ear Number ($\times 10^4$ Ear ha^{-1})	Grain Number per Ear	100-Grain Weight (g)	Yield (t ha^{-1})
Year (Y)	NS	***	***	NS
CK	NS	***	***	***
Density (D)	***	***	***	***
N application rate (N)	NS	***	***	***
Y × CK	NS	***	NS	NS
Y × D	***	***	***	NS
Y × N	NS	***	NS	NS
D × N	NS	***	NS	*
Y × D × N	NS	NS	NS	NS

Note: NS: no significant difference; *: $p < 0.05$; ***: $p < 0.001$.

The relationship between the N application rate and yield exhibited a linear + plateau trend (Figure 3). In 2022, the highest yield of 10.70 t ha^{-1} was observed at a N application rate of 190 kg ha^{-1}, and in 2023, the highest yield of 13.59 t ha^{-1} was recorded at a N application rate of 255 kg ha^{-1} for D2 density. At D1 density, in 2023, the highest yield of 10.87 t ha^{-1} was achieved with a N application rate of 224 kg ha^{-1}, while at D2 density, the highest yield of 13.95 t ha^{-1} was obtained with a N application rate of 276 kg ha^{-1}. Beyond the optimal N application rate, further increases did not significantly boost yield, indicating a wastage of nitrogen fertilization resources.

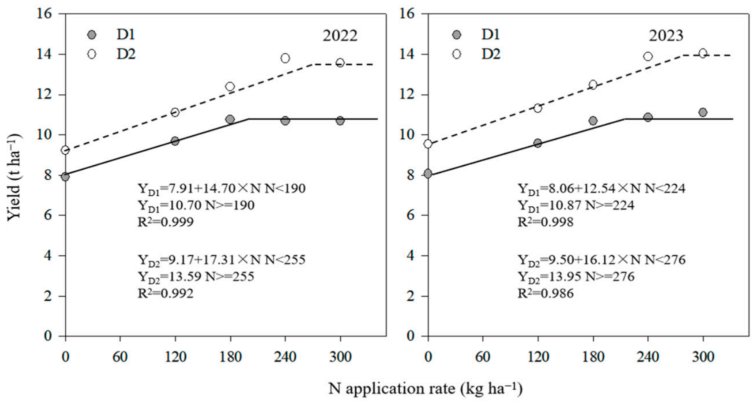

Figure 3. Relationship between grain yield and N application rate in 2022–2023.

3.3. Evapotranspiration (ET), Water Use Efficiency (WUE), and Irrigation Water Use Efficiency (IWUE)

Significant differences were observed in ET among different years, fertilization methods, densities, and N application rates (Tables 5 and 6). In 2023, ET was 24.77% higher than in 2022, primarily due to higher rainfall. The ET of CK was 17.26% higher than that of surface drip fertilization, mainly attributed to greater irrigation. ET increased with higher planting density and N application rates. The plant density, N application rate, and their interaction significantly influenced WUE and IWUE. As plant density increased from D1 to D2, the WUE and IWUE rose by 10.36% and 15.33%, respectively. The WUE initially increased and then decreased with increasing N application rates, while the IWUE exhibited a similar trend to yield. At D1 density, the WUE and IWUE increased gradually with N application rates ranging from 0 to 180 kg ha^{-1}, whereas at D2 density, the WUE and IWUE increased gradually with N application rates ranging from 0 to 240 kg ha^{-1}. The WUE and IWUE of D1N2 were 40.37% and 66.92% higher, respectively, than those of CK, while the WUE and IWUE of D2N3 were 58.74% and 115.55% higher, respectively, than CK.

Table 5. The effects of different treatments on the evapotranspiration (ET), water use efficiency (WUE), and irrigation water use efficiency (IWUE) of maize.

Year	Density	Treatment	ET (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
2022	D1	CK	532 a	1.86 d	4.17 d
		N0	341 e	2.32 c	5.11 c
		N1	368 d	2.63 ab	6.24 b
		N2	399 c	2.69 a	6.93 a
		N3	422 b	2.53 b	6.89 a
		N4	451 a	2.37 c	6.89 a
	D2	N0	388 e	2.38 c	5.95 d
		N1	412 d	2.69 b	7.16 c
		N2	440 c	2.81 b	7.99 b
		N3	462 b	2.99 a	8.89 a
		N4	488 a	2.75 b	8.65 a

Table 5. *Cont.*

Year	Density	Treatment	ET (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
2023	D1	CK	635 a	1.55 d	4.11 d
		N0	448 e	1.80 c	5.20 c
		N1	474 d	2.02 ab	6.17 b
		N2	505 c	2.11 a	6.89 a
		N3	528 b	2.05 a	7.00 a
		N4	557 a	1.99 b	7.16 a
	D2	N0	494 e	1.93 e	6.15 d
		N1	519 d	2.18 d	7.29 c
		N2	547 c	2.28 c	8.05 b
		N3	568 b	2.44 a	8.95 a
		N4	594 a	2.36 b	9.05 a

Note: ET: evapotranspiration; WUE: water use efficiency; IWUE: irrigation water use efficiency. D1: 6.0×10^4 plants ha^{-1}; D2: 9.0×10^4 plants ha^{-1}. CK: traditional planting method, 300 kg ha^{-1}; N0: no nitrogen application; N1: 120 kg ha^{-1}; N2: 180 kg ha^{-1}; N3: 240 kg ha^{-1}; N4: 300 kg ha^{-1}. Different letters in the same column indicate significant differences between different treatments ($p < 0.05$).

Table 6. Analysis of variance of year, fertilization method, density, and N application rate on evapotranspiration (ET), water use efficiency (WUE), and irrigation water use efficiency (IWUE).

Variation Source	ET (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
Year (Y)	***	***	NS
CK	***	***	***
Density (D)	***	***	***
N application rate (N)	***	***	***
Y × CK	NS	NS	NS
Y × D	NS	NS	NS
Y × N	NS	NS	NS
D × N	NS	**	*
Y × D × N	NS	NS	NS

Note: NS: no significant difference; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

3.4. Nitrogen Partial Factor Productivity (PFP_N) and Nitrogen Agronomic Efficiency (AE_N)

The planting density, N application rate, and their interaction significantly influenced PFP_N and AE_N (Table 7). Increasing planting density led to significant increases in both PFP_N and AE_N (Figures 4 and 5), by 20.33% and 30.52%, respectively. At the same density, PFP_N gradually decreased while AE_N initially increased and then decreased with increasing N application rates. PFP_N and AE_N were significantly higher under surface drip fertilization compared to CK. At D1 density, PFP_N and AE_N for N2 were significantly higher than for N3 and N4, with increases of 91.61% and 244.31% compared to CK. At D2 density, PFP_N and AE_N for N3 were significantly higher than for N4, with increases of 85.58% and 323.40%, respectively, compared to CK.

Table 7. Analysis of variance of year, fertilization method, density, and N application rate on nitrogen partial factor productivity (PFP_N) and nitrogen agronomic efficiency (AE_N).

Variation Source	PFP_N (kg kg^{-1})	AE_N (kg kg^{-1})
Year (Y)	NS	NS
CK	*	***
Density (D)	***	***
N application rate (N)	***	***

Table 7. *Cont.*

Variation Source	PFP_N (kg kg^{-1})	AE_N (kg kg^{-1})
Y × CK	NS	NS
Y × D	NS	NS
Y × N	NS	*
D × N	***	***
Y × D × N	NS	NS

Note: NS: no significant difference; *: $p < 0.05$; ***: $p < 0.001$.

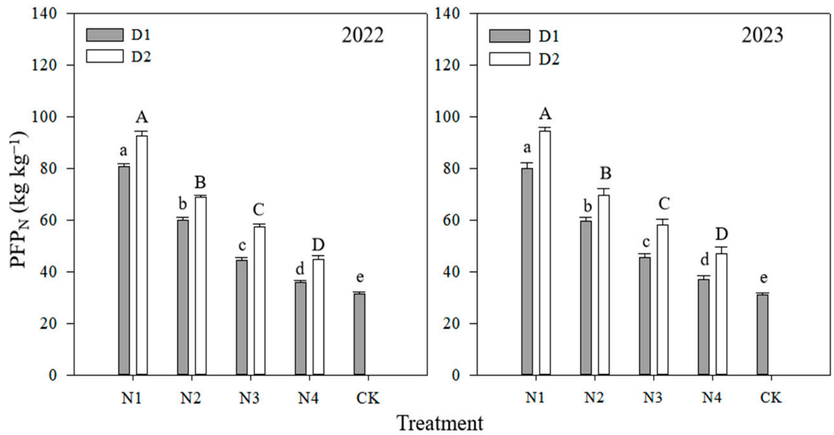

Figure 4. The nitrogen partial factor productivity (PFP_N) of the different treatments from 2022 to 2023. Different lowercase letters indicate significant differences between different treatments of D1 density ($p < 0.05$). Different uppercase letters indicate significant differences between different treatments of D2 density ($p < 0.05$).

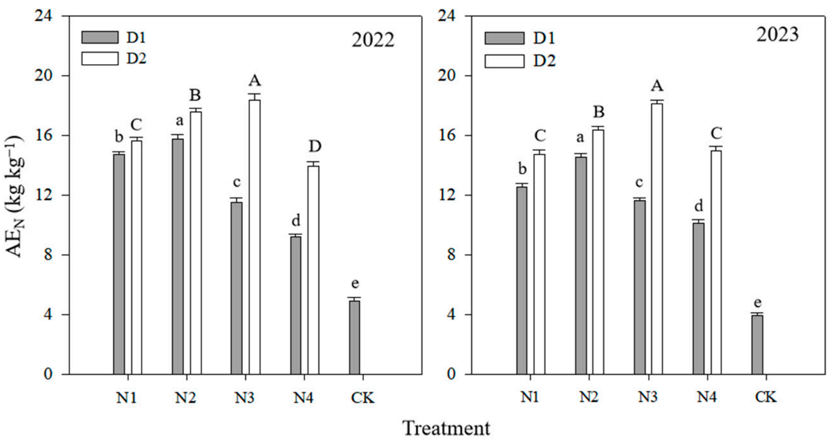

Figure 5. The nitrogen agronomic efficiency (AE_N) of the different treatments from 2022 to 2023. Different lowercase letters indicate significant differences between different treatments of D1 density ($p < 0.05$). Different uppercase letters indicate significant differences between different treatments of D2 density ($p < 0.05$).

3.5. Economic Benefit

Significant differences were observed in the economic benefit and output/input across different planting densities and N application amounts (Table 8). Notably, variations were primarily evident in fertilizer costs among treatments sharing the same density but differing in N application rates. While seed costs, irrigation costs, pipe costs, and labor costs remained constant, elevated N application rates correlated with increased fertilization costs. Distinctions also emerged among various fertilization methods, encompassing pipeline and labor costs, fertilizer costs, and irrigation costs. Traditional fertilization techniques reduced pipeline and labor expenses but escalated fertilizer and irrigation amounts. Conversely, surface drip fertilization under D2N3 conditions obtained the highest economic benefit and output/input, showcasing a 72.11% and 61.01% increase compared to CK. Although higher planting densities and nitrogen applications amplified seed and fertilizer costs, they concurrently boosted grain output value, thereby enhancing economic outcomes and output/input. Specifically, the D2N3 treatment saw a 39.34% and 30.29% increase in economic benefit and the output/input ratio, respectively, compared to D1N2.

Table 8. The effects of different treatments on the economic benefit and output/input of maize.

Year	Density	Treatment	Economic Benefit ($\times 10^4$ CNY ha^{-1})	Output/Input	Grain Output Value ($\times 10^4$ CNY ha^{-1})	Seed Cost (CNY ha^{-1})	Irrigation Cost (CNY ha^{-1})	Fertilizer Cost (CNY ha^{-1})	Pipeline and Labor Cost (CNY ha^{-1})
2022	D1	CK	1.45 b	1.81 c	2.25	525	600	3300	1500
		N0	1.18 c	1.64 d	1.90	525	300	1800	2323
		N1	1.54 b	1.98 bc	2.32	525	300	2400	2323
		N2	1.77 a	2.18 a	2.58	525	300	2700	2323
		N3	1.72 a	2.05 b	2.56	525	300	3000	2323
		N4	1.67 a	1.94 bc	2.56	525	300	3300	2323
	D2	N0	1.47 d	1.97 d	2.21	787.5	300	1800	2323
		N1	1.86 c	2.30 c	2.66	787.5	300	2400	2323
		N2	2.14 b	2.56 b	2.97	787.5	300	2700	2323
		N3	2.44 a	2.82 a	3.31	787.5	300	3000	2323
		N4	2.32 ab	2.59 b	3.22	787.5	300	3300	2323
2023	D1	CK	1.40 cd	1.72 b	2.22	525	600	3300	1500
		N0	1.22 d	1.69 b	1.94	525	300	1800	2323
		N1	1.52 bc	1.95 ab	2.30	525	300	2400	2323
		N2	1.75 ab	2.16 a	2.56	525	300	2700	2323
		N3	1.77 ab	2.10 a	2.61	525	300	3000	2323
		N4	1.79 a	2.06 a	2.66	525	300	3300	2323
	D2	N0	1.54 c	2.07 b	2.29	787.5	300	1800	2323
		N1	1.91 b	2.36 ab	2.71	787.5	300	2400	2323
		N2	2.16 b	2.58 abc	2.99	787.5	300	2700	2323
		N3	2.47 a	2.85 a	3.33	787.5	300	3000	2323
		N4	2.47 a	2.76 ab	3.37	787.5	300	3300	2323

Note: D1: 6.0×10^4 plants ha^{-1}; D2: 9.0×10^4 plants ha^{-1}. CK: traditional planting method, 300 kg ha^{-1}; N0: no nitrogen application; N1: 120 kg ha^{-1}; N2: 180 kg ha^{-1}; N3: 240 kg ha^{-1}; N4: 300 kg ha^{-1}. Different letters in the same column indicate significant differences between different treatments ($p < 0.05$).

4. Discussion

Dry matter formation and the HI serve as pivotal determinants for grain yield [30]. Increasing planting density has been shown to augment dry matter weight and yield [31]. Optimal fertilization and judicious density augmentation are recognized as essential strategies for enhancing maize yield [28]. Our findings corroborate previous studies, demonstrating that a heightened planting density fosters an increased grain yield primarily through augmented ear numbers, a trend observed by Wei et al. [32]. Specifically, compared to D1, D2 exhibited a significant 21.17% average yield increase. Notably, our investigation identified an optimal grain yield range (13.78–13.88 t ha^{-1}) achievable with D2 planting density (9.0×10^4 plants ha^{-1}) paired with N application rate N3 (240 kg ha^{-1}). We observed a linear + plateau relationship between the N application rate and grain yield under integrated drip irrigation with water and fertilizer. Incremental N application facilitated yield augmentation by enhancing both grain number and weight [33]. However, a saturation point was observed, suggesting that excessive N may hinder root development, diminishing nutrient and water absorption efficiency, and thus curbing further yield increases [34]. Furthermore, our results indicated that under surface drip fertilization, treatments like D2N3 exhibited a significantly higher DMA, HI, and grain yield compared to other treatments. Augmenting planting density and optimizing nitrogen application significantly enhanced maize dry matter accumulation and yield. Notably, surface drip fertilization, compared to traditional fertilization methods, significantly improved the dry matter, grain number per ear, grain weight, and, ultimately, grain yield. In parallel, the grain yield of D2N3 surpassed that of Xu et al. [12] by 19.56% under conventional fertilization at the same planting density. This improvement can be attributed to integrated drip irrigation, ensuring nitrogen supply at crucial maize growth stages, thereby enhancing the post-anthesis dry matter accumulation and subsequent grain yield [35]. In contrast, traditional single-base fertilization often leads to early-stage nitrogen abundance, vigorous early plant growth, subsequent nitrogen leaching losses due to irrigation or rainfall, and post-silking nitrogen deficiency, impeding dry matter accumulation and yield. These findings align with prior research outcomes [36–38].

The findings of this experiment underscored the superior water and nitrogen use efficiency of surface drip fertilization compared to CK, primarily attributed to reduced irrigation and N application amounts, thereby mitigating water evaporation, infiltration, and fertilizer loss [39,40]. Surface drip fertilization facilitates direct water and nitrogen delivery to the root zone, enhancing maize absorption efficiency, thereby conserving water and reducing nitrogen usage [41,42]. Moreover, it ensures optimal soil moisture and nutrient levels through controlled frequent irrigation and nitrogen applications during grain filling, thereby enhancing water and nitrogen productivity [17,18,43]. Our research found that the ET of the drip irrigation treatment was significantly lower than that of the flood irrigation treatment, because the flood irrigation treatment had a higher irrigation amount, while the research conducted by Mohammed et al. [44] in the United States showed that the ET of subsurface drip irrigation was significantly higher than that of furrow irrigation, because the irrigation efficiency of subsurface drip irrigation was higher, the water was directly transported to the root zone of crops, and the distribution was more uniform, while furrow irrigation could only wet the surface of soil, thus affecting the infiltration rate of farmland water.

Under surface drip fertilization, WUE, IWUE, PFP_N, and AE_N exhibited significant increases with rising planting density. With escalating N application rates, the IWUE initially increased but plateaued thereafter, while PFP_N gradually declined. The WUE and AE_N exhibited an initial increase followed by a decrease. Notably, the highest water and nitrogen productivity were attained under D2N3. This can be attributed to heightened density enhancing plant population and N fostering root growth and canopy expansion, thereby optimizing nutrient uptake from applied fertilizers and available organic nitrogen sources, ultimately enhancing water and fertilizer utilization efficiency [22,45]. However, excessive N application may lead to nitrate accumulation in the soil, compromising soil moisture and diminishing water and fertilization use efficiency [46].

Previous studies have highlighted a synergistic relationship between water and nitrogen. Nonetheless, this experiment exclusively explored the impacts of maize yield, water and N use efficiency, and economic benefits under varying planting densities and N application rates. Further investigations are warranted to explore the effects of irrigation amounts and the interaction between irrigation amounts and N application rates on yield, water, and fertilizer use efficiency.

In maize cultivation, attaining multiple objectives simultaneously poses challenges [45]. To ensure food security and bolster agricultural productivity, increasing planting density emerges as a dependable strategy to elevate summer maize yield per unit area in the Huang-Huai-Hai region. Nevertheless, augmenting planting density necessitates greater irrigation water and fertilizer inputs to satisfy the heightened water and nutrient demands of dense populations [47]. Conventional fertilization methods escalate production costs and water and fertilizer losses while diminishing water and fertilizer utilization efficiency and economic benefits. Employing surface drip fertilization coupled with tailored N provision based on plant requirements, amalgamating heightened planting density with reduced N application, can effectively enhance maize yield benefits and nitrogen utilization efficiency [12,25]. Li et al. [29] observed that shallow buried surface drip fertilization incurred significantly higher input costs, net income, and input/output ratios compared to conventional farmer practices. Our experiment revealed an 18.67% increase in grain yield under surface drip fertilization compared to traditional methods, with the optimum N application rate being 20% lower. Despite the increased costs associated with pipelines and labor, surface drip fertilization curtailed fertilizer and irrigation volumes while augmenting yields. Consequently, it yielded higher economic benefits and output/input compared to traditional methods, which is consistent with the results obtained by Wang et al. [48] in the northeast of China.

Under our experimental setup, the D2N3 treatment yielded the highest, requiring 60 kg ha^{-1} more N than the D1N2 treatment. This not only conserved 70 mm of irrigation water and 60 kg ha^{-1} compared to CK but also optimized the maize population's water and fertilizer utilization efficiency. It mitigated cost escalation and environmental pollution resulting from excessive fertilization, thereby realizing synergic enhancements in yield, water and nitrogen use efficiency, and economic returns.

5. Conclusions

In the summer maize belt of the Huang-Huai-Hai region in China, employing surface drip fertilization showcased a notable trend: maize yield followed a linear + plateau trajectory as N application rates increased, peaking at a maximum yield of 13.78–13.88 t ha^{-1}. This approach also yielded high water use efficiency (24.42–29.85 kg m^{-3}), nitrogen agronomic efficiency (18.11–19.00 kg kg^{-1}), and economic benefits (2.44 $\times$ 10^{4}–2.47 $\times$ 10^{4} CNY ha^{-1}) with D2N3. Consequently, the implementation of surface drip fertilization, coupled with a planting density of 9.0 $\times$ 10^{4} plants ha^{-1} and N application rate of 240 kg ha^{-1}, effectively facilitated the accumulation of dry matter post-anthesis and its subsequent distribution to grains. This approach enhanced the dry matter weight of the plant population, thereby enhancing grain yield, water and fertilizer utilization efficiency, and economic benefits. On the basis of this experiment, we can continue to study the influence of different irrigation amounts on maize production.

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