

Article

Effects of Interaction Between Planting Density and Nitrogen Application Rate on Maize (*Zea mays* L.) Canopy Structure, Photosynthetic Characteristics, and Water–Nitrogen Productivity

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Abstract

Increasing planting density is an effective strategy for improving maize (*Zea mays* L.) productivity, but it can also intensify interplant competition and canopy shading. Enhanced nitrogen application may help offset these negative effects. A two-year field experiment was conducted in the Hexi Corridor, an arid region of northwestern China, using a full factorial design with three planting density levels D1 (75,000 plants ha^{−1}), D2 (90,000 plants ha^{−1}), and D3 (105,000 plants ha^{−1}), and three nitrogen application levels N1 (198 kg ha^{−1}), N2 (264 kg ha^{−1}), and N3 (330 kg ha^{−1}). The aim was to clarify how the interaction between planting density and nitrogen application regulates maize canopy structure and affects resource use efficiency in arid areas. The results showed that planting density, nitrogen rate, and their interaction significantly affected canopy structure, photosynthetic traits, grain yield, and water and nitrogen use efficiency. From the perspective of each growth stage, combinations of medium and high planting density and nitrogen application levels facilitated the optimization of maize canopy structure, promoted plant growth and dry matter accumulation, and elevated leaf SPAD values. Meanwhile, treatment D2N2 exhibited the most prominent improvement in maize yield components, with grain yield increased by 1.44–35.58% on average across experimental years. This treatment also sustained superior water and nitrogen use efficiency, achieving an average water use efficiency of 3.53 kg·m^{−3} and an average partial factor productivity of nitrogen of 53.41 kg·kg^{−1}. Comprehensive multi-index evaluation verified that D2N2 represented the optimal cultivation regime. This regime could reduce nitrogen fertilizer input by 20% while fully exploiting light and heat resources inherent to arid regions. Collectively, this study establishes a viable green and high-efficiency cultivation paradigm for maize production with high yield, reduced fertilizer input and water conservation, and delivers critical theoretical and technical references for the sustainable intensification of maize cultivation in arid regions of northwest China.

Keywords: planting density; nitrogen fertilizer; maize canopy structure; yield; water–nitrogen productivity; photosynthetic characteristics



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1. Introduction

Maize (*Zea mays* L.) ranks among the world's leading food crops, and it is indispensable for sustaining global food security and supporting the animal feed industry [1]. However, with continued global population growth and changes in dietary structure, the imbalance between food supply and demand has become increasingly severe. According to projections from the Food and Agriculture Organization (FAO) of the United Nations, the world's agricultural output must rise by 70% by 2050 to meet rising demand [2]. For a long time, agricultural production has relied on high inputs of water and fertilizer to maintain yield, which has not only resulted in low resource use efficiency and environmental pollution [3,4], but has also been challenged by shrinking arable land [5], extreme climate events, and increasing resource constraints [6]. Under these circumstances, developing sustainable agricultural production technologies to safeguard food security has become a major global priority.

In recent years, increasing planting density has become an important strategy for improving maize yield in major maize-producing regions worldwide [7]. A proper increase in planting density can optimize canopy structure, enhance light interception in the middle and lower canopy, and improve population-level light interception and photosynthetic efficiency, thereby promoting dry matter accumulation [8,9]. Meanwhile, higher planting density can increase the proportion of canopy transpiration and reduce ineffective soil evaporation [10], thereby improving resource use efficiency and promoting crop growth. Furthermore, dense planting increases maize photosynthetic area [11], facilitates population-scale carbohydrate accumulation [12], and sustains root nutrient capture networks as well as soil carbon sequestration [13–15]. However, dense planting has clear dual effects. Excessively low planting density results in an irrational canopy structure and waste of light and heat resources, whereas excessively high planting density intensifies interplant competition for resources [12], disrupts canopy light distribution, and markedly reduces light interception in the middle and lower canopy. As a result, light intensity in the lower canopy may fall below the light compensation point, inducing premature leaf senescence and significantly reducing leaf relative chlorophyll contents (SPAD values) as well as individual and population photosynthetic capacity [16,17]. When planting density exceeds the regional ecological threshold, it may also weaken lodging resistance, reduce the proportion of photosynthates transported to grains, affect grain-filling rate, shorten the filling period, and ultimately reduce grain quality and marginal economic returns [12,18]. Therefore, optimization of planting density to maximize yield and economic return while simultaneously improving resource use efficiency remains a key issue in maize production.

Nitrogen is one of the core elements involved in crop photosynthesis and physiological metabolism, and plays an important regulatory role in root development, canopy formation, and dry matter accumulation in maize [19,20]. Increasing nitrogen application has therefore become an important agronomic practice for improving crop yield. Nitrogen application can promote nitrogen accumulation in maize plants, accelerate plant growth and development [21], and increase leaf area index, leaf SPAD value, and photosynthetic capacity. It can also help expand the photosynthetic source, prolong the duration of photosynthesis and the filling period, and promote grain dry matter accumulation [22]. However, the contribution of nitrogen fertilizer to maize yield also shows dual effects. Insufficient nitrogen application inhibits key physiological processes such as chlorophyll synthesis and carbon–nitrogen metabolism, accelerates leaf senescence, suppresses vegetative growth, and causes imbalance in population growth, thereby reducing light use efficiency. It can also affect root spatial distribution, weaken root uptake of nutrients and water, increase grain abortion, and ultimately decrease yield [23,24]. By contrast, excessive nitrogen application may overstimulate nitrogen metabolism in leaves, reduce the plant carbon-to-nitrogen

ratio, impair the transport and export efficiency of photosynthates, inhibit the development of photosynthetic organs and reproductive growth, disrupt the source–sink balance, and shorten the filling duration, thereby also reducing yield [24,25]. In addition, excessive nitrogen input may lead to a series of ecological and environmental problems, including agricultural non-point source pollution, soil acidification, and increased greenhouse gas emissions [26]. Therefore, achieving green and sustainable agricultural development while maintaining high grain yield has become an important challenge in modern agriculture.

Northwestern China is rich in light and heat resources. Among these regions, the Hexi Corridor, supported by well-developed irrigation systems, has become an important commercial grain-producing area in Gansu Province. Irrigation provides stable water conditions for agricultural production in this region, where the maize planting area has remained at approximately 286.86 thousand hectares, with an economic yield of 2.4295 million tons [27]. However, maize production in this area still faces several prominent problems, including excessive nitrogen input, low fertilizer use efficiency, and insufficient utilization of light and heat resources. Current studies on maize planting density and nitrogen management have mainly focused on single-factor regulatory effects. Specifically, in the Hexi Oasis irrigation region, the synergistic mechanisms of density and nitrogen interactions governing canopy structure, photosynthetic physiological traits, and water and nitrogen use efficiency remain poorly understood. Against this background, a two-year field experiment was conducted in the Hexi Corridor to improve the utilization efficiency of fertilizer, light and heat resources via density and nitrogen coupling regulation. We hypothesized that optimal combinations of planting density and nitrogen application can optimize maize canopy structure and light utilization capacity in arid oasis irrigation ecosystems, thereby achieving high yield and resource efficiency while reducing nitrogen fertilizer input. This study aimed to determine the optimal combination of planting density and nitrogen rate for maize cultivation in arid oasis irrigation areas of northwest China, and to elucidate the regulatory mechanism by which canopy structure and photosynthetic characteristics mediate grain yield and water–nitrogen use efficiency.

2. Materials and Methods

2.1. Study Area

A two-year field experiment was carried out between April 2023 and October 2024 at the Yimin Irrigation Experiment Station, Minle County, Zhangye, Gansu Province, China (100°43' E, 38°39' N; Figure 1). The experimental area is characterized by a typical continental desert steppe climate, with arid conditions, low precipitation, large diurnal temperature variation, abundant solar radiation, and intense surface evaporation. The region receives more than 2966 h of sunshine annually, with a mean annual air temperature of 7.6 °C, an accumulated temperature above 0 °C of 3053.6 °C, an average annual precipitation of approximately 200 mm, a frost-free period of 150 d, and an average annual evaporation of about 1625.2 mm. During the experimental period, meteorological data, including precipitation and air temperature during the maize growing season, were continuously monitored using a DZZ6 automatic weather station (Zhonghuan Tianyi Meteorological Instrument Co., Ltd., Tianjin, China) installed within the experimental field (Figure 2).

The soil in the experimental area is classified as light loam. The bulk density of the 0–60 cm cultivated soil layer was approximately 1.44 g cm^{−3}, and the field water-holding capacity was 22%. The groundwater table in the region is deeper than 20 m, with no groundwater recharge or soil salinization observed. Before maize sowing, the basic chemical and physical properties of the 0–60 cm cultivated soil layer were determined, and the results are presented in Table 1.

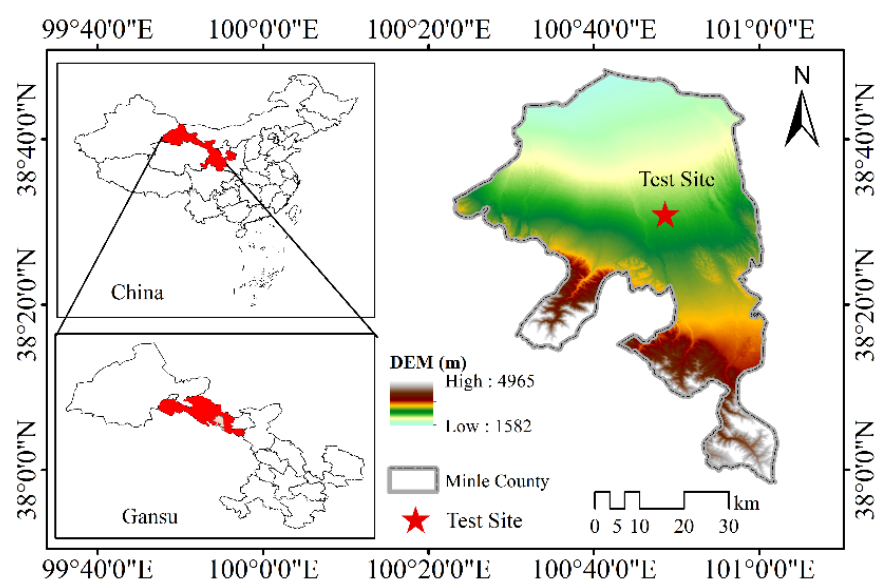


Figure 1. Study area location map.

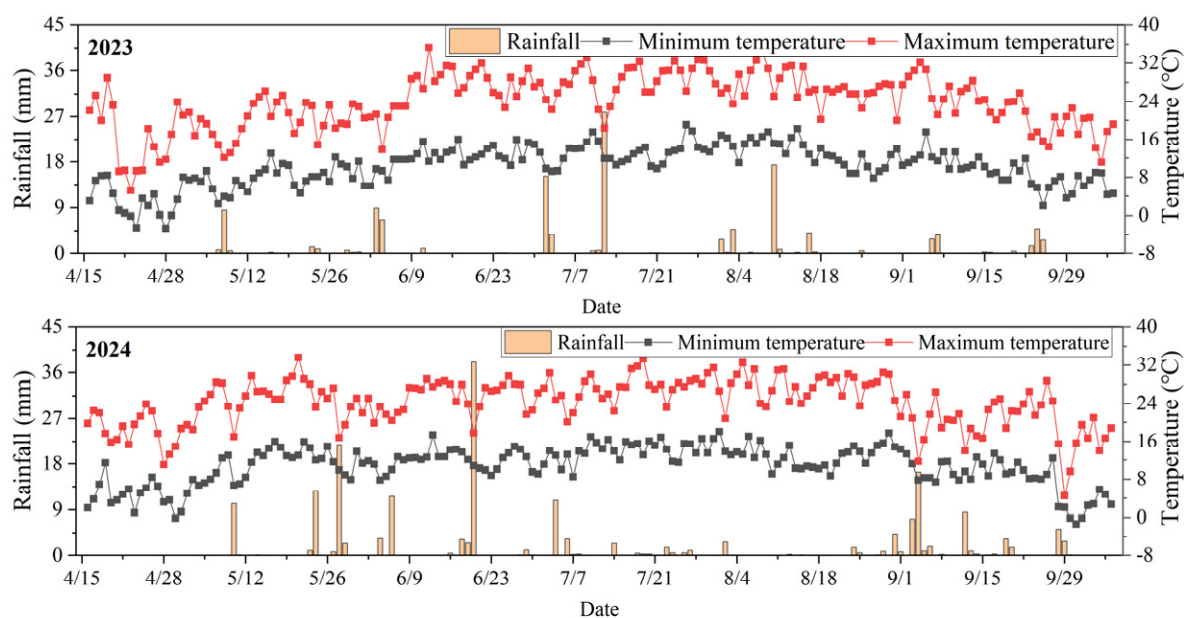


Figure 2. Meteorological data during the maize growing season.

Table 1. Soil physicochemical properties of the experimental site.

Soil Depth (cm)	Organic Matter (g·kg ⁻¹)	Nitrate Nitrogen (mg·kg ⁻¹)	Total Nitrogen (g·kg ⁻¹)	Available Phosphorus (mg·kg ⁻¹)	Available Potassium (mg·kg ⁻¹)	pH
0–20	12.11	30.84	0.82	27.83	127.52	8.9
20–40	9.82	22.78	0.68	21.44	93.93	7.81
40–60	7.95	15.52	0.54	16.35	72.85	7.74

2.2. Experimental Design

In this study, the maize hybrid employed for field planting was Xianyu 335. The experiment followed a two-factor randomized complete block design, with planting density and nitrogen application rate as the two tested variables. Three nitrogen rates (calculated as pure nitrogen) were implemented: 198 kg ha⁻¹ (N1), 264 kg ha⁻¹ (N2), and 330 kg ha⁻¹

(N3). Meanwhile, three planting densities were established: 75,000 plants ha⁻¹ (D1), 90,000 plants ha⁻¹ (D2), and 105,000 plants ha⁻¹ (D3). All planting density and nitrogen rate treatments followed the spring maize cultivation technical specifications published by the Gansu Provincial Department of Agriculture and Rural Affairs (<https://nync.gansu.gov.cn/> (accessed on 20 July 2026)). These two factors yielded nine treatment combinations in total. Each treatment was replicated three times, and a 0.5 m-wide buffer row was established between adjacent plots to prevent boundary interference. The area of each individual plot was 20 m², with dimensions of 4 m × 5 m.

A uniform row spacing of 40 cm was used for all treatments, and planting density was regulated by adjusting plant spacing. The corresponding plant spacings for D1, D2, and D3 were 33, 28, and 24 cm, respectively. To ensure accurate control of planting density, maize was sown manually by hill seeding.

Seeding was performed on 15 April 2023 and 17 April 2024, and crop harvesting was completed on 7 October in both growing seasons. All maize plants were grown under plastic film mulching combined with drip irrigation, with one drip irrigation tape arranged between each pair of maize rows. Before sowing, all plots received basal applications of 120 kg ha⁻¹ calcium superphosphate (P₂O₅ ≥ 16%) and 80 kg ha⁻¹ potassium sulfate (K₂O ≥ 51%). Meanwhile, 30% of the total nitrogen fertilizer was applied as basal nitrogen. The remaining 70% of nitrogen was supplied via integrated water-fertilizer scheduling, with 30% topdressed at the jointing stage and 40% at the filling stage through drip irrigation (Table 2). All other agronomic management measures followed the local standard practices for maize production.

Table 2. Experimental design.

Treatment	Planting Density (Plants ha ⁻¹)	Nitrogen Application Rate (kg ha ⁻¹)
D1N1	75,000	198 (40% reduction)
D1N2		264 (20% reduction)
D1N3		330
D2N1	90,000	198
D2N2		264
D2N3		330
D3N1	105,000	198
D3N2		264
D3N3		330

Note: D is the planting density of maize (plant ha⁻¹), and N is the nitrogen fertilizer supply (kg ha⁻¹) in the whole growing season of maize.

2.3. Measurements and Methods

2.3.1. Maize Canopy Structure

At the seedling, jointing, boot, and filling stages, three maize plants with uniform growth were randomly selected from each plot and transported to the laboratory for the determination of canopy structure-related traits. Plant height was determined using a steel measuring tape with a precision of 0.1 cm, measured from the base of the stem to the apex of the naturally growing plant. Individual leaves were detached sequentially, and the length and maximum width of each leaf were recorded. Leaf area was calculated according to the formula: leaf area = leaf length × leaf width × 0.75 [25]; LAI = leaf area per plant × number of plants per unit land area/unit land area. Following completion of the morphological measurements, each maize plant was divided into roots, stems, leaves, and cob. All samples were immediately subjected to 105 °C for 30 min to inactivate enzymes, then dried to a constant weight at 80 °C. The dry weight of each organ was measured using a precision electronic balance, and total dry matter accumulation per plant was calculated accordingly.

2.3.2. Net Photosynthetic Rate and Leaf Relative Chlorophyll Content (SPAD Value)

At the seedling, jointing, booting, and filling stages of maize, the net photosynthetic rate (P_n) of the uppermost fully expanded leaves was determined using an LI-6400XT portable photosynthesis system (LI-COR, Lincoln, NE, USA). Measurements were performed between 9:00 and 11:30 a.m. on sunny days without cloud cover. The flow rate was fixed at $500 \mu\text{mol s}^{-1}$; reference CO_2 concentration was controlled at $400 \mu\text{mol mol}^{-1}$. For each plot, three uniform plants were randomly chosen for determination, and the average value was used for statistical analysis. In parallel, leaf relative chlorophyll content was assessed with a SPAD-502 chlorophyll meter (Minolta Corp., Ramsey, NJ, USA). The final SPAD value for each plot was calculated as the mean of three individual plants.

2.3.3. Yield and Yield Components

At physiological maturity, ten consecutive and representative maize plants were sampled from the central rows of each plot and transported to the laboratory for the determination of yield components. After the ears were separated from the plants, the number of kernel rows per ear, number of kernels per row, and 100-kernel weight were measured. For grain yield determination, twenty consecutive maize plants were sampled from the central rows of each plot, and all ears were harvested and transported to the laboratory for threshing. The fresh grain weight was subsequently recorded. Grain moisture content was measured using a SYS-PM-8188 grain moisture meter (Liaoning Saias Technology Co., Ltd., Liaoning, China), and grain weight was adjusted to a standard moisture content of 14%. Finally, grain yield per hectare was calculated based on the standardized grain weight of the twenty sampled plants and the actual plant population density of the corresponding treatment.

2.3.4. Water and Nitrogen Use Efficiency

Crop evapotranspiration (ET) was calculated via the soil water balance equation as follows:

$$ET = P + I + W - D - R + \Delta W$$

where ET denotes crop evapotranspiration (mm), P denotes precipitation (mm), I denotes irrigation volume (mm), and W denotes groundwater recharge (mm). Given the groundwater depth exceeding 20 m at the test site, W was taken as 0. D is deep drainage (mm), which can be neglected. ΔW represents the change in soil water storage across the 0–100 cm soil profile (mm), and R is surface runoff (mm). R equaled 0 as no runoff occurred throughout the experiment.

Water use efficiency was calculated as follows:

$$WUE = \frac{Y}{ET} \quad (1)$$

where WUE denotes water use efficiency ($\text{kg} \cdot \text{m}^{-3}$), Y denotes grain yield ($\text{kg} \cdot \text{ha}^{-1}$), and ET denotes evapotranspiration (mm).

Partial factor productivity of nitrogen was calculated as follows:

$$NPFP = \frac{Y}{N} \quad (2)$$

where $NPFP$ denotes partial factor productivity of nitrogen ($\text{kg} \cdot \text{kg}^{-1}$), Y denotes grain yield ($\text{kg} \cdot \text{ha}^{-1}$), and N denotes nitrogen application rate ($\text{kg} \cdot \text{ha}^{-1}$).

2.4. Data Analysis

Data were organized and calculated using Microsoft Excel 2019 (Microsoft Corporation, Redmond, DC, USA). Normality test and homogeneity of variance test were conducted for all datasets of each treatment prior to statistical analysis. Statistical comparisons of significant differences among treatments were conducted via the LSD multiple range test embedded in SPSS 26.0 software (IBM, Inc., New York, NY, USA), and figures were generated using Origin 2024 (Origin Lab, Corp., Hampton, MA, USA). The comprehensive evaluation of maize was conducted using Yaahp (Meta Decision Software Technology Co., Ltd., Corp., Taiyuan, China) and MATLAB (Version R2023 b, MathWorks, Corp., Natick, MA, USA) software.

3. Results

3.1. Effects of Interaction Between Planting Density and Nitrogen Application Rate on Maize Growth Dynamics

3.1.1. Plant Height

Planting density and nitrogen application significantly affected maize plant height at all growth stages ($p < 0.05$ or $p < 0.01$). Their interactive effect was not significant at the seedling and jointing stages, while plant height showed a continuous increasing trend throughout the growth period (Figure 3). Across all growth stages, all treatments exhibited a consistent trend: increasing nitrogen application facilitated maize vegetative growth under identical planting density. No significant differences in plant height were detected between the N2 and N3 nitrogen rates, whereas N3 yielded substantially taller plants relative to N1. Taking the filling stage as an example, plant height rose by an average of 7.16% from N1 to N2, while the increment from N2 to N3 was merely 1.05%. These results indicate that increasing nitrogen application effectively promoted maize canopy growth, but its effect on canopy structure improvement diminished markedly with further increases in nitrogen rate.

Under identical nitrogen supply levels, comparable trends were observed across all growth stages: plant height increased with rising planting density, yet the promotional effect was limited under the highest density D3. For instance, at the grain-filling stage, the average plant height increased by 5.94% from D1 to D2, whereas the increment from D2 to D3 was merely 1.84%. This suggests that a moderate increase in planting density can optimize maize canopy structure, whereas excessively high planting density intensifies interplant competition for water and nutrients, thereby gradually weakening its positive effect on canopy structure. Under the interactive regulation of nitrogen application and planting density, the D3N3 treatment produced the greatest plant height at all growth stages, although no significant differences were observed between D3N3 and D3N2, D2N2, or D2N3.

3.1.2. Leaf Area Index (LAI)

The leaf area index (LAI) of maize displayed an initial increase followed by a gradual decrease across the entire growing season. LAI was strongly affected by planting density, nitrogen fertilization, and their interaction ($p < 0.01$), whereas their interactive impact was not statistically significant at the seedling and jointing stages (Figure 4). The dynamic variations in leaf area index (LAI) from the seedling to grain-filling stages exhibited consistent trends across the two experimental years. From seedling to jointing stage, increasing nitrogen application elevated LAI under the same planting density. At the jointing stage, LAI increased by an average of 13.90% from N1 to N2, with only a 2.08% average increment from N2 to N3. From the heading to grain-filling stage, the D3N3 combination produced

a lower LAI value, yet no statistically significant difference was detected relative to the D3N2 treatment.

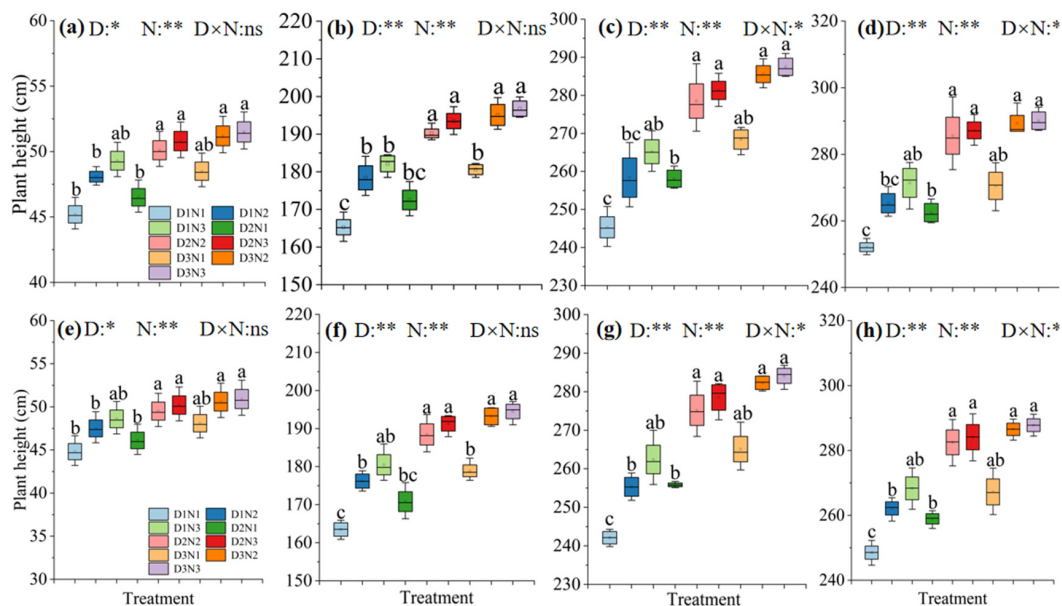


Figure 3. Effects of the interaction between planting density and nitrogen application rate on maize plant height. (a–d) represent 2023, (e–h) represent 2024. (a,e) represent seeding stage, (b,f) represent jointing stage, (c,g) represent boot stage, (d,h) represent filling stage. D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$; ns indicates no significant difference at $p > 0.05$. Different lowercase letters within the same growth stage indicate significant differences among treatments.

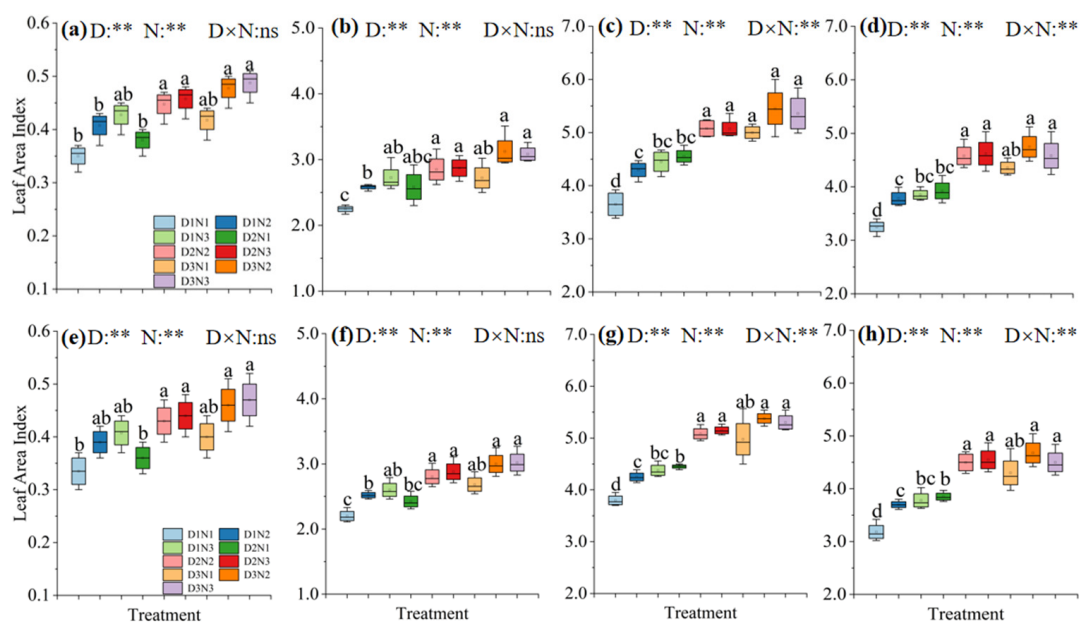


Figure 4. Effects of the interaction between planting density and nitrogen application rate on maize leaf area index throughout the growing season. (a–d) represent 2023, (e–h) represent 2024. (a,e) represent seeding stage, (b,f) represent jointing stage, (c,g) represent boot stage, (d,h) represent filling stage. D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. ** indicates significance at $p < 0.01$; ns indicates no significant difference at $p > 0.05$. Different lowercase letters within the same growth stage indicate significant differences among treatments.

Planting density also acted as a critical regulator of leaf area index (LAI). Elevated planting density generally increased LAI, showing a response pattern analogous to nitrogen supply from the seedling to jointing stage. At the jointing stage, LAI rose by an average of 10.47% from D1 to D2 and 7.34% from D2 to D3. Nevertheless, excessively high planting density reduced LAI at the grain-filling stage. Under the interactive effects of planting density and nitrogen application, LAI was highest under D3N3 from the seedling stage to the boot stage, whereas at the filling stage it was highest under D3N2, with no significant difference between the two treatments.

3.1.3. Dry Matter Accumulation per Plant

Efficient dry matter accumulation provides the material basis for achieving high maize yield. As shown in Figure 5, dry matter accumulation per plant increased continuously with crop development and reached a maximum at the filling stage, with a two-year mean ranging from 282.85 to 356.85 g plant⁻¹. Dry matter accumulation in maize grown under arid conditions was significantly affected by nitrogen fertilization, planting density, and their interaction ($p < 0.01$), although the interactive effect did not reach statistical significance at the seedling stage.

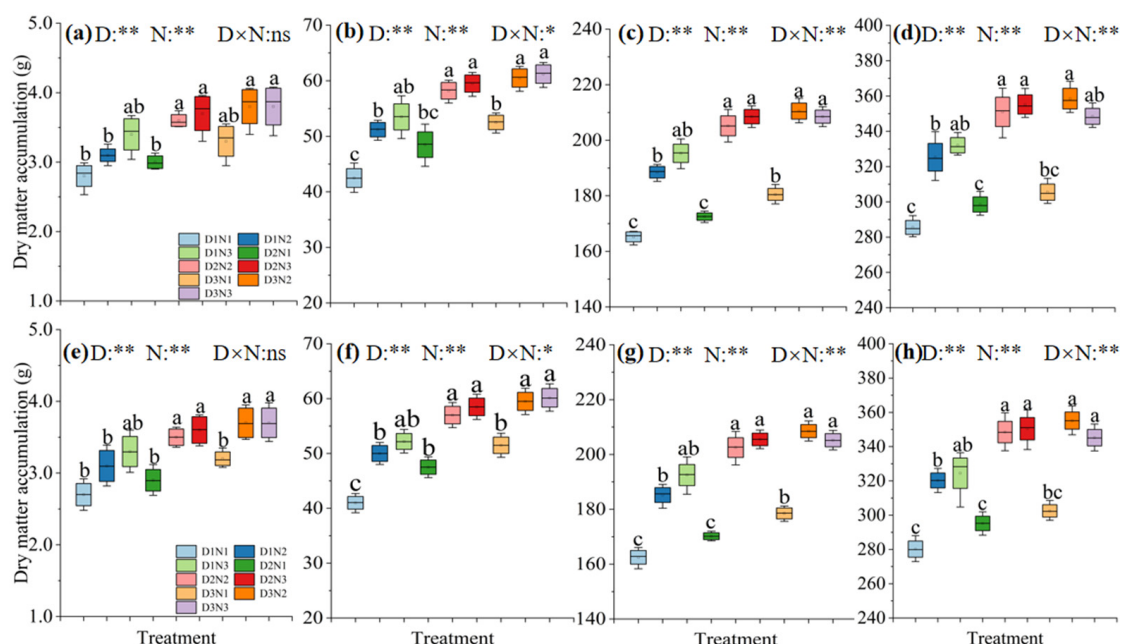


Figure 5. Effects of the interaction between planting density and nitrogen application rate on dry matter accumulation per plant throughout the maize growing season. (a–d) represent 2023, (e–h) represent 2024, (a,e) represent seedling stage, (b,f) represent jointing stage, (c,g) represent boot stage, (d,h) represent filling stage. D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$; ns indicates no significant difference at $p > 0.05$. Different lowercase letters within the same growth stage indicate significant differences among treatments.

Under a fixed planting density, increased nitrogen supply promoted dry matter accumulation of maize from the seedling to jointing stage. At the jointing stage, dry matter weight increased by a two-year average of 18.66% from N1 to N2, with only a 2.53% average increment from N2 to N3, indicating that the promoting effect on dry matter accumulation weakened as nitrogen application rates further rose. From jointing to heading stage, the N3 nitrogen level under D3 planting density restrained dry matter accumulation instead, though no significant difference was observed compared with the D3N2 treatment.

Planting density was another key factor governing dry matter production of maize in arid regions. Under identical nitrogen application rates, increasing planting density facilitated maize dry matter accumulation, with consistent variation trends observed from the seedling to jointing stage. For example, at the jointing stage, dry matter accumulation increased by a two-year average of 10.47% from D1 to D2 and 4.92% from D2 to D3. However, excessively high planting density intensified interplant competition for water, nutrients and light resources during the grain-filling stage, which only slightly improved dry matter accumulation or even exerted an inhibitory effect. Under the interactive effects of nitrogen application and planting density, treatments combining D3 with N2 or N3 produced the highest dry matter accumulation at all growth stages, and no significant differences were observed among these combined treatments.

3.2. Effects of Interaction Between Planting Density and Nitrogen Application Rate on Photosynthetic Performance of Maize

3.2.1. Net Photosynthetic Rate

Photosynthesis is the fundamental physiological basis for grain yield formation in maize. Nitrogen application, planting density, and their interaction had significant or highly significant effects on leaf net photosynthetic rate (Pn) ($p < 0.05$ or $p < 0.01$) (Table 3). Only the single effect of nitrogen application and the interaction between nitrogen and planting density at the seedling stage had no significant effect on leaf Pn (Table 3). As the growth period progressed, leaf Pn first increased and then decreased, with all treatments reaching a peak at the boot stage (Figure 6).

Table 3. Analysis of variance of Pn in maize and two-year mean values.

	Treatment	Seeding Stage	Jointing Stage	Boot Stage	Filling Stage
Mean	D1N1	18.3	26.3	28.3	20.3
	D1N2	20.0	30.0	32.3	24.0
	D1N3	20.5	30.8	33.0	24.5
	D2N1	19.0	28.0	30.0	22.0
	D2N2	21.3	32.3	34.5	26.3
	D2N3	21.5	32.5	34.8	26.0
	D3N1	19.3	27.0	28.7	20.0
	D3N2	21.0	31.3	33.3	24.3
	D3N3	20.8	31.0	32.5	23.0
Year	Growth period	Seeding stage	Jointing stage	Boot stage	Filling stage
2023	D	ns	**	**	**
	N	**	**	**	**
	D × N	ns	*	**	**
2024	D	ns	**	**	**
	N	**	**	**	**
	D × N	ns	*	**	**

Note: D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$; ns indicates no significant difference at $p > 0.05$.

Increasing nitrogen application improved leaf Pn under the same planting density. However, the D3N3 treatment suppressed leaf photosynthetic capacity and exhibited lower Pn values relative to the D2N2 treatment, though the difference was statistically non-significant. These findings indicated that an optimal combination of planting density and nitrogen supply could enhance photosynthetic efficiency, whereas further in-

creases in density and nitrogen rate yielded marginal improvements or even inhibited photosynthetic performance.

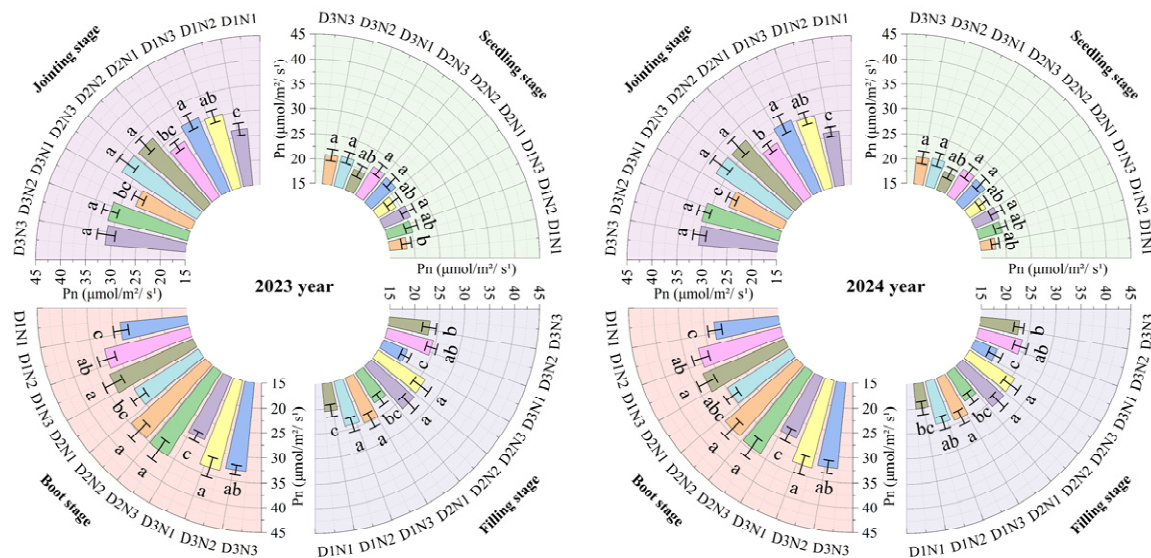


Figure 6. Effects of the interaction between planting density and nitrogen application rate on net photosynthetic rate throughout the maize growing season. D, planting density; N, nitrogen application rate.

Planting density also significantly regulated Pn of maize in arid regions, and leaf Pn generally declined with the rise in planting density, with consistent response trends across all treatments. For instance, at the jointing stage, the two-year average Pn increased by 6.61% from D1 to D2, whereas a 3.77% reduction was observed from D2 to D3. This suggests that a moderate increase in planting density can improve leaf photosynthetic performance, whereas excessively high planting density aggravates insufficient light interception within the canopy and intensifies interplant nutrient competition, thereby significantly reducing leaf Pn. Under the interaction between nitrogen application and planting density, leaf Pn was highest under D2N3 from the seedling stage to the boot stage, whereas at the filling stage it was highest under D2N2. Statistically comparable leaf Pn values were detected between the two treatments during the remaining growth stages.

3.2.2. SPAD

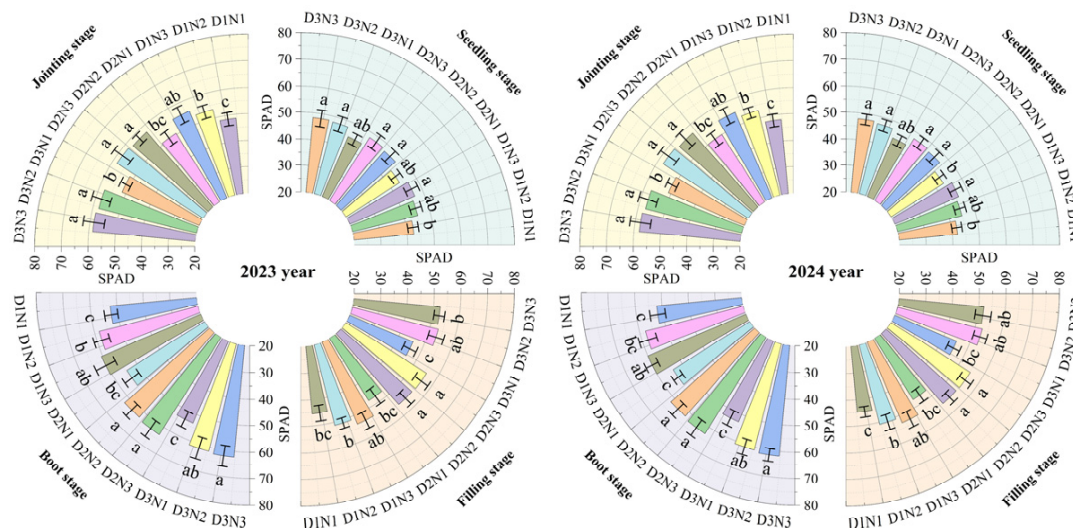
Chlorophyll is the primary pigment involved in crop photosynthesis and plays an essential role in regulating key photosynthetic and physiological processes. The SPAD value serves as a critical index for assessing the relative chlorophyll concentration in leaves. The seasonal pattern of leaf SPAD value in maize was consistent with that of Pn, with both reaching a maximum at the boot stage. Leaf SPAD value was significantly influenced by nitrogen fertilization, planting density, and their interactive effect ($p < 0.05$ or $p < 0.01$, Table 4). However, the single effect of nitrogen application and the interaction between nitrogen and planting density at the seedling stage, as well as their interaction at the boot stage, had no significant effect on SPAD value (Figure 7).

Under identical planting density, leaf SPAD values of maize increased with rising nitrogen application rates from the seedling to heading stage. At the jointing stage, SPAD values rose by an average of 12.02% from N1 to N2 and only 2.24% from N2 to N3. During the grain-filling stage; however, the D3N3 treatment exhibited slightly lower SPAD readings relative to D3N2, without significant statistical differences between the two treatments.

Table 4. Analysis of variance of SPAD in maize and two-year mean values.

	Treatment	Seeding Stage	Jointing Stage	Boot Stage	Filling Stage
Mean	D1N1	42.3	48.3	52.3	45.3
	D1N2	45.0	53.0	58.0	51.0
	D1N3	46.3	55.3	60.3	53.3
	D2N1	43.5	50.3	54.3	47.3
	D2N2	47.0	57.3	62.3	55.3
	D2N3	47.8	58.0	63.0	55.5
	D3N1	44.3	51.3	53.3	45.5
	D3N2	47.5	57.5	61.3	53.0
	D3N3	48.0	58.3	62.0	52.3
Year	Growth period	Seeding stage	Jointing stage	Boot stage	Filling stage
2023	D	ns	*	**	**
	N	**	**	**	**
	D × N	ns	ns	*	*
2024	D	ns	*	**	**
	N	**	**	**	**
	D × N	ns	ns	*	*

Note: D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$; ns indicates no significant difference at $p > 0.05$.

**Figure 7.** Effects of the interaction between planting density and nitrogen application rate on SPAD values throughout the maize growing season.

Planting density also exerted a significant effect on leaf SPAD values. From the seedling to jointing stage, increasing planting density elevated SPAD readings under the same nitrogen supply level. For example, SPAD values increased by an average of 5.75% from D1 to D2 and merely 0.91% from D2 to D3 at the jointing stage. Nevertheless, excessively high planting density aggravated interplant competition for light, water and nutrients during the heading and grain-filling stages, thereby reducing leaf SPAD values. Under the interaction between nitrogen application and planting density, leaf SPAD value was highest under D3N3 at the seedling and jointing stages, whereas it was highest under

D2N3 at the boot and filling stages. The two treatments exhibited statistically similar leaf SPAD values with no significant discrepancy.

3.3. Effects of Interaction Between Planting Density and Nitrogen Application Rate on Maize Yield and Its Components

In the arid study environment, both planting density and nitrogen fertilization, as well as their interaction, exerted statistically significant impacts on maize yield and yield components ($p < 0.05$ or $p < 0.01$, Table 5). Notably, grain fraction was only significantly affected by nitrogen application at the $p < 0.05$ threshold. Mean-value analysis under the same nitrogen level showed that increasing nitrogen application was beneficial to grain yield formation in maize. From N1 to N2, the two-year mean values of kernel rows per ear, 100-grain weight, grain fraction, and grain yield increased by 7.45%, 10.30%, 2.82%, and 17.91%, respectively. Under planting densities D2 and D3, kernel rows per cob, 100-kernel weight, grain allocation ratio and grain yield exhibited decreasing trends when the nitrogen application rate reached 330 kg ha^{-1} (N3), whereas no significant differences were detected compared with N2. These results indicate that excessive nitrogen application in maize production under arid conditions not only failed to increase yield, but instead significantly inhibited yield formation.

Table 5. Effects of the interaction between planting density and nitrogen application rate on maize yield and its components.

Year	Treatment		Kernel Rows	100-Grain Weight (g)	Percentage of Kernel to Cob (%)	Yield (t/ha)	
2023	D1N1		15.20 c	32.50 c	82.50 b	10.50 d	
	D1N2		16.10 b	35.20 b	84.20 ab	11.80 c	
	D1N3		16.30 b	35.80 ab	84.80 a	12.10 bc	
	D2N1		15.80 bc	34.20 b	83.50 b	11.50 c	
	D2N2		17.50 a	38.50 a	86.50 a	14.20 a	
	D2N3		17.30 a	38.20 a	86.20 a	14.00 a	
	D3N1		16.20 b	33.50 bc	83.20 b	11.80 c	
	D3N2		17.10 a	36.80 ab	85.50 a	13.80 ab	
	D3N3		16.80 ab	35.50 b	84.50 ab	13.20 b	
	Mean						
	Kernel rows 100-grain weight Percentage of kernel to cob Yield	D1	D2	D3	N1	N2	N3
		15.87	16.87	16.70	15.73	16.90	16.80
		34.50	36.97	35.27	33.40	36.83	36.50
		83.83	85.40	84.40	83.07	85.40	85.17
		11.47	13.23	12.93	11.27	13.27	13.10
	Significant						
	D		*	*	ns	**	
	N		**	**	*	**	
	D × N		*	*	ns	**	
2024	D1N1		15.00 d	32.00 c	82.00 b	10.30 d	
	D1N2		16.00 b	34.80 b	83.80 ab	11.60 c	
	D1N3		16.20 b	35.20 ab	84.20 ab	11.90 bc	
	D2N1		15.60 c	33.80 b	83.00 b	11.30 c	
	D2N2		17.30 a	38.00 a	86.00 a	14.00 a	
	D2N3		17.10 a	37.80 a	85.80 a	13.80 ab	
	D3N1		16.10 b	33.00 bc	82.80 b	11.60 c	

Table 5. Cont.

Year	Treatment		Kernel Rows	100-Grain Weight (g)	Percentage of Kernel to Cob (%)	Yield (t/ha)	
	D3N2		16.90 ab	36.20 ab	85.00 a	13.60 b	
	D3N3		16.40 b	35.00 b	84.00 ab	13.00 b	
	Mean						
		D1	D2	D3	N1	N2	N3
	Kernel rows	15.73	16.67	16.47	15.57	16.73	16.57
	100-grain weight	34.00	36.53	34.73	32.93	36.33	36.00
	Percentage of kernel to cob	83.33	84.93	83.93	82.60	84.93	84.67
	Yield	11.27	13.03	12.73	11.07	13.07	12.90
	Significant						
		D	*	*	ns	**	
	N	**	**	*	**		
	D × N	*	*	ns	**		

Note: D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. Values followed by different lowercase letters within the same column indicate significant differences at $p < 0.05$. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$; ns indicates no significant difference at $p > 0.05$.

Planting density also had a significant regulatory effect on maize yield components and grain yield, and its effect showed a trend similar to that of nitrogen application. From D1 to D2, the two-year mean values of kernel rows per cob, 100-kernel weight, grain fraction, and grain yield increased by 6.12%, 7.30%, 1.89%, and 15.54%, respectively. From D2 to D3, however, the corresponding values decreased by 1.09%, 4.76%, 1.17%, and 2.28%, respectively. This suggests that a moderate increase in planting density can promote yield improvement, whereas excessively high density intensifies interplant competition for resources, suppresses grain dry matter accumulation, and ultimately leads to yield reduction.

Under the combined regulation of the interaction between nitrogen application and planting density, kernel rows per cob, 100-kernel weight, grain fraction, and grain yield all performed best under the D2N2 treatment, under which all these parameters reached their maximum values; however, no significant differences were observed compared with treatment D2N3.

3.4. Effects of Interaction Between Planting Density and Nitrogen Application Rate on Water and Nitrogen Use Efficiency of Maize

Water use efficiency and nitrogen partial factor productivity in maize were both significantly influenced by nitrogen fertilization, planting density, and their interactive effect ($p < 0.05$ or $p < 0.01$) (Figure 8). Under the D1 planting density, increasing nitrogen application significantly improved water use efficiency. However, under the D2 and D3 planting densities, excessive nitrogen application reduced water use efficiency, with the two-year mean water use efficiency under N3 decreasing by 1.42% and 4.38%, respectively, compared with that under N2. The effect of planting density on water use efficiency showed a pattern similar to that of nitrogen application. Under the N2 and N3 nitrogen levels, the two-year mean water use efficiency under D3 were 2.84% and 5.76% lower, respectively, than that under D2. These results indicate that excessively high planting density and excessive nitrogen application intensify competition for water among plants, thereby significantly reducing maize water use efficiency.

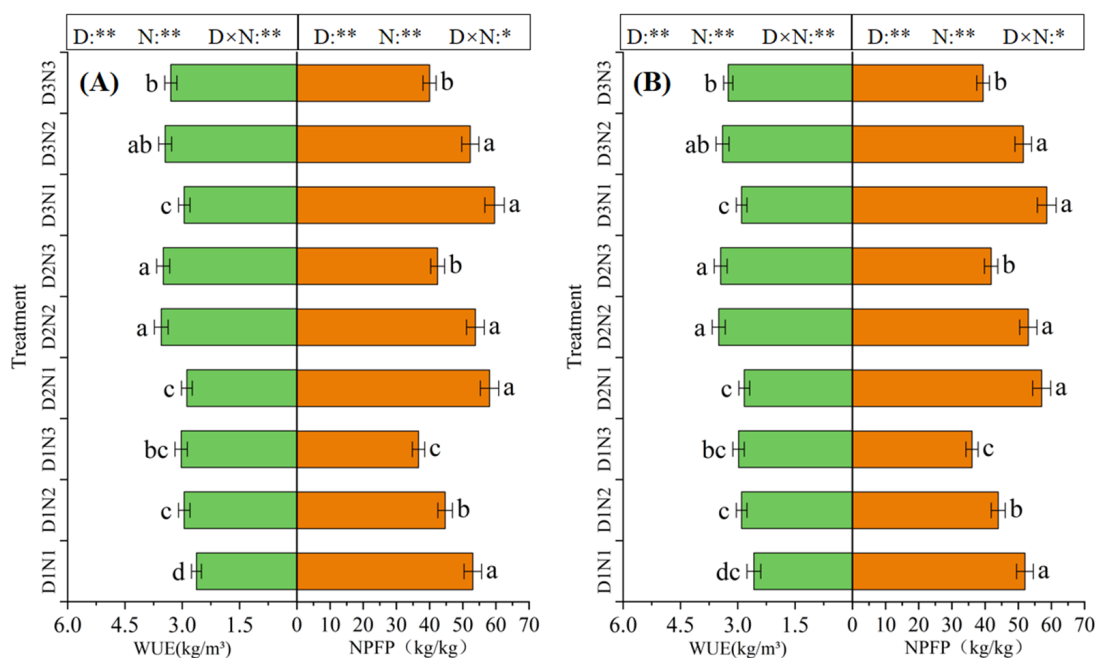


Figure 8. Effects of the interaction between planting density and nitrogen application rate on water and nitrogen use efficiency of maize. (A) represents 2023, (B) represents 2024. D, planting density; N, nitrogen application rate; D × N, the interaction between planting density and nitrogen application rate. * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$. Different lowercase letters within the same growth stage indicate significant differences among treatments.

Under the same planting density, partial factor productivity of nitrogen in maize showed a continuous decline with increasing nitrogen application. Mean-value analysis under the same nitrogen level showed that partial factor productivity of nitrogen decreased by 11.57% on average over the two years from N1 to N2, and further decreased by 21.02% from N2 to N3. Meanwhile, excessively high planting density intensified competition for nutrient resources among plants, which also reduced partial factor productivity of nitrogen in maize. Under the combined regulation of nitrogen application, planting density, and their interaction, the D2N2 treatment showed the highest water use efficiency, with a two-year mean of $3.53 \text{ kg} \cdot \text{m}^{-3}$, whereas the D3N1 treatment achieved the highest partial factor productivity of nitrogen, with a two-year mean of 59.10 kg/kg .

3.5. Comprehensive Evaluation of Maize Performance

3.5.1. Analytic Hierarchy Process (AHP) Model for Comprehensive Evaluation

A hierarchical framework for the comprehensive assessment of maize performance was established using Yaahp software (Figure 9). The target layer of the comprehensive evaluation (C) consisted of four criterion layers: growth traits (C_1); photosynthetic traits (C_2); yield traits (C_3); and water and nitrogen use traits (C_4). The growth trait criterion included two indicator layers: dry matter accumulation (C_{11}) and leaf area index (C_{12}). The photosynthetic trait criterion included two indicator layers: net photosynthetic rate (C_{21}) and leaf SPAD value (C_{22}). The yield trait criterion included two indicator layers: 100-kernel weight (C_{31}) and grain yield (C_{32}). The water and nitrogen use trait criterion included two indicator layers: water use efficiency (C_{41}) and partial factor productivity of nitrogen (C_{42}).

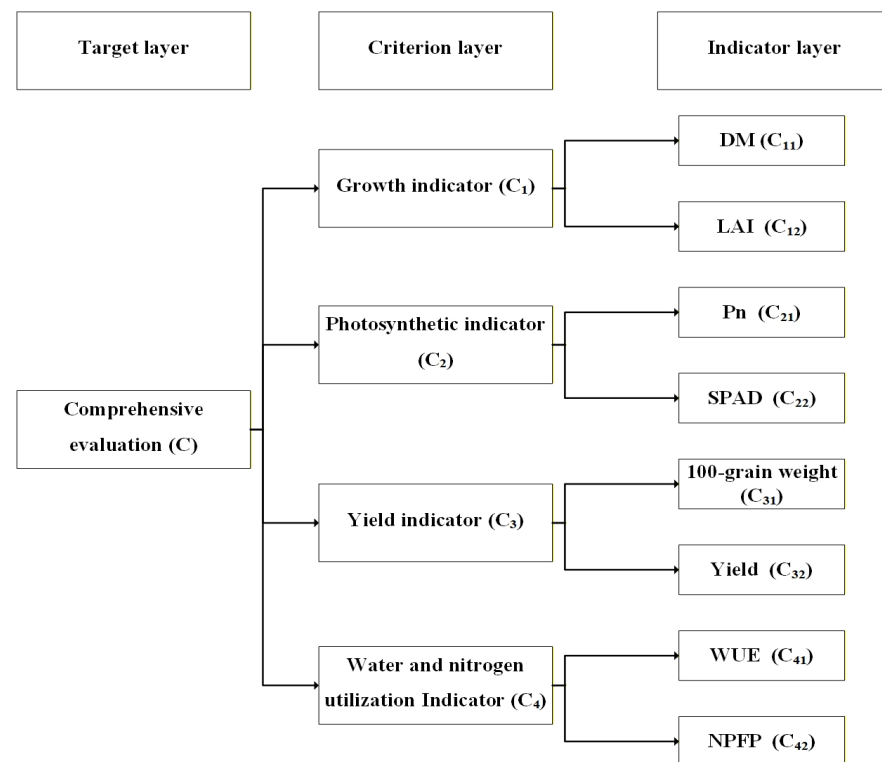


Figure 9. AHP model of comprehensive evaluation indices for maize. DM, dry matter accumulation; LAI, leaf area index; Pn, net photosynthetic rate; WUE, water use efficiency; NPFP, partial factor productivity of nitrogen.

3.5.2. Indicator Weights

(1) After establishing the hierarchical model, the AHP was used to determine the weights. A judgment matrix was constructed based on the 1–10 scale method, and the relative importance of each indicator was assigned according to the model. Consistency tests were then performed for the matrices. The judgment matrices for growth traits, photosynthetic traits, yield traits, and water and nitrogen use traits are shown in Figure 10.

$$C = \begin{bmatrix} 1.0000 & 0.3333 & 1.2000 & 1.5000 \\ 3.0000 & 1.0000 & 1.0000 & 2.0000 \\ 0.8333 & 1.0000 & 1.0000 & 1.5000 \\ 0.6667 & 0.5000 & 0.6667 & 1.0000 \end{bmatrix} \quad C_1 = \begin{bmatrix} 1.0000 & 1.2000 \\ 0.8333 & 1.0000 \end{bmatrix} \quad C_2 = \begin{bmatrix} 1.0000 & 0.5000 \\ 2.0000 & 1.0000 \end{bmatrix}$$

$$C_3 = \begin{bmatrix} 1.0000 & 0.2500 \\ 4.0000 & 1.0000 \end{bmatrix} \quad C_4 = \begin{bmatrix} 1.0000 & 2.0000 \\ 0.5000 & 1.0000 \end{bmatrix}$$

The consistency ratio (C_R) values of the above judgment matrices were all less than 0.1, indicating that the constructed matrices were reliable and reasonable (Table 6, where $\lambda_{\max}$ denotes the maximum eigenvalue). The results showed that SPAD had the highest weight, followed by grain yield, whereas NPFP had the lowest weight.

(2) Determination of weights based on entropy weight method

The weight of each maize indicator was determined using the entropy weight approach, and the corresponding weighting results are summarized in Table 7. As shown in the table, SPAD had the highest weight, followed by Pn, whereas LAI had the lowest weight.

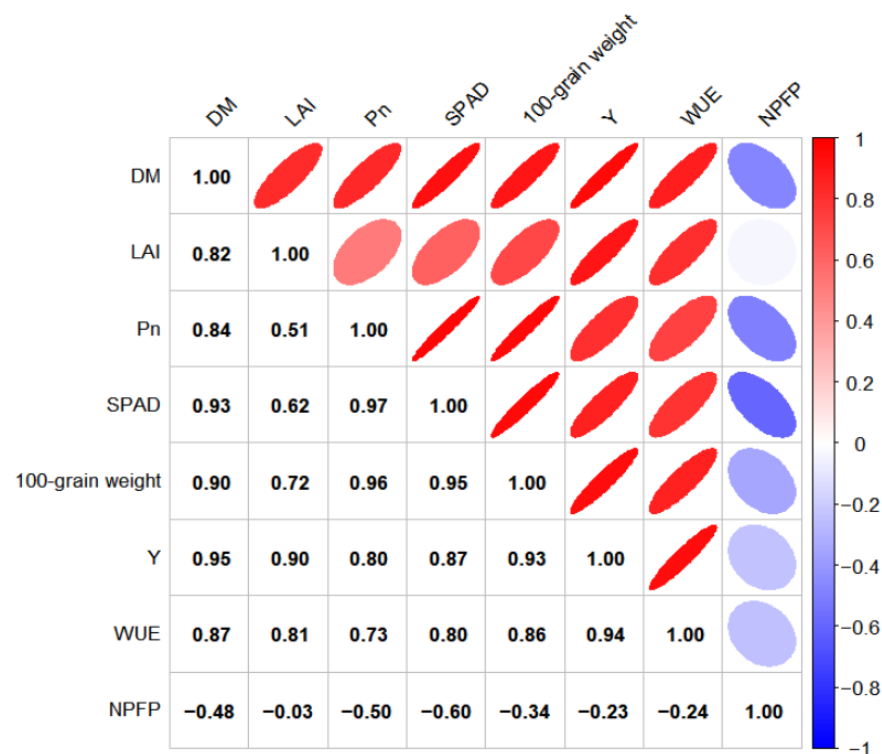


Figure 10. Correlation matrix of maize traits. DM, dry matter accumulation; LAI, leaf area index; Pn, net photosynthetic rate; WUE, water use efficiency; NPFP, partial factor productivity of nitrogen.

Table 6. Weights of evaluation indicators calculated using the AHP method.

Hierarchy Level	Index	Local Weight	Final Weight	Consistency Test Ratio
Destination layer	Grow	0.2108	0.2108	$C_R = 0.0580 < 0.1$ $\lambda_{\max} = 4.1549$
	Photosynthetic	0.3801	0.3801	
	Yield	0.2512	0.2512	
	Water and nitrogen use efficiency	0.1579	0.1579	
Criterion layer C_1	Dry matter accumulation quantity	0.5455	0.1150	$C_R = 0.0000 < 0.1$ $\lambda_{\max} = 2.0000$
	LAI	0.4545	0.0958	
Criterion layer C_2	Pn	0.3333	0.1267	$C_R = 0.0000 < 0.1$ $\lambda_{\max} = 2.0000$
	SPAD	0.6667	0.2534	
Criterion layer C_3	100-grain weight	0.2000	0.0502	$C_R = 0.0000 < 0.1$ $\lambda_{\max} = 2.0000$
	Yield	0.8000	0.2010	
Criterion layer C_4	WUE	0.6667	0.1053	$C_R = 0.0000 < 0.1$ $\lambda_{\max} = 2.0000$
	NPFP	0.3333	0.0526	

Table 7. Determination of weights for individual maize indicators based on the entropy weight method.

Index	C_{11}	C_{12}	C_{21}	C_{22}
Weight	0.1171	0.0949	0.1425	0.1587
Index	C_{31}	C_{32}	C_{41}	C_{42}
Weight	0.1231	0.1160	0.1162	0.1316

(3) Combined weighting based on game theory

To enhance the scientific validity and robustness of indicator weighting while minimizing subjective bias in the evaluation process, a foundational weight dataset was established

by integrating weighting results derived from the analytic hierarchy process (AHP) and entropy weight method, where $W = \sum \alpha_K \times W_K^T (\alpha_K > 0)$, α_K , and W_K represent the basic weight set and the weights derived from the AHP and entropy weight methods, respectively. A combined weight optimization model based on game theory was then established, and the corresponding game-theoretic model $\min \left\| \sum \alpha_j \times \mu_j^T - \mu_i^T \right\|, i = 1, 2$ was derived. Using MATLAB, the normalized combination coefficients were obtained as $\alpha_1^* = 1.0836$ and $\alpha_2^* = -0.0836$. Accordingly, the combined weight vector $W = \sum \alpha_K^* \times \mu_K^T$ was determined, and the final results are presented in Table 8. As shown in the table, SPAD had the highest weight, followed by grain yield, whereas Pn had the lowest weight.

Table 8. Weights of individual maize indicators based on game theory combination weighting.

Index	C ₁₁	C ₁₂	C ₂₁	C ₂₂
Weight	0.1148	0.0959	0.1254	0.2613
Index	C ₃₁	C ₃₂	C ₄₁	C ₄₂
Weight	0.0442	0.2081	0.1044	0.0460

3.5.3. Comprehensive Evaluation of Maize Based on TOPSIS Method

Following the TOPSIS approach with combined weighting, the original decision matrix was initially normalized to generate a standardized matrix, followed by the construction of a weighted decision matrix. The positive/negative ideal solutions and the corresponding closeness coefficient (C_i) for each treatment were then computed; detailed outcomes are presented in Table 9. The D2N2 treatment exhibited the highest comprehensive closeness coefficient, followed by the D3N2 treatment, whereas the D1N1 treatment had the lowest value and showed the poorest performance.

Table 9. Comprehensive evaluation and ordering of maize based on the TOPSIS method.

Treatment	C ₁₁	C ₁₂	C ₂₁	C ₂₂	C ₃₁	C ₃₂
D1N1	0.2873	0.2565	0.2878	0.2954	0.3038	0.2772
D1N2	0.3280	0.2984	0.3410	0.3330	0.3297	0.3119
D1N3	0.3355	0.3044	0.3481	0.3477	0.3344	0.3199
D2N1	0.3015	0.3100	0.3126	0.3085	0.3203	0.3039
D2N2	0.3560	0.3623	0.3730	0.3607	0.3603	0.3759
D2N3	0.3588	0.3658	0.3695	0.3624	0.3580	0.3705
D3N1	0.3088	0.3443	0.2842	0.2971	0.3132	0.3119
D3N2	0.3625	0.3762	0.3446	0.3460	0.3438	0.3652
D3N3	0.3523	0.3623	0.3268	0.3411	0.3321	0.3492
S ⁺	0.3625	0.3762	0.3730	0.3624	0.3603	0.3759
S [−]	0.2873	0.2565	0.2842	0.2954	0.3038	0.2772
Treatment	C ₄₁	C ₄₂	D ⁺	D [−]	C _i	Order
D1N1	0.2776	0.3562	0.0858	0.0235	0.2153	9
D1N2	0.3117	0.3005	0.0534	0.0408	0.4332	6
D1N3	0.3203	0.2466	0.0530	0.0482	0.4763	5
D2N1	0.3043	0.3904	0.0612	0.0404	0.3973	8
D2N2	0.3757	0.3622	0.0096	0.0866	0.9000	1
D2N3	0.3704	0.2856	0.0251	0.0820	0.7653	3
D3N1	0.3117	0.4007	0.0625	0.0475	0.4320	7
D3N2	0.3650	0.3519	0.0181	0.0783	0.8122	2
D3N3	0.3490	0.2692	0.0383	0.0632	0.6226	4
S ⁺	0.3757	0.4007				
S [−]	0.2776	0.2466				

4. Discussion

4.1. Effects of Planting Density and Nitrogen Application on Maize Canopy Structure

A well-developed canopy structure can increase light interception and help form a high-yield crop population [28]. LAI is an important indicator reflecting crop canopy structure and light use efficiency. Increasing planting density may intensify nutrient competition, whereas nitrogen application can alleviate this competitive effect [29]. During the early growth stages of maize, nutrient demand is relatively low. Increased planting density facilitates light penetration into the middle and lower canopy layers, while nitrogen application promotes leaf expansion; their synergistic effects consequently result in a higher LAI [30,31]. This is consistent with the results of the present study, in which the D3N3 treatment improved maize canopy structure and produced a higher LAI from the seedling stage to the jointing stage. However, from tasseling to grain-filling, the D3 planting density intensified mutual shading among leaves. Excessive nitrogen application also induced excessive vegetative growth, disrupted the source–sink balance within the canopy, and accelerated premature leaf senescence, ultimately resulting in a decline in LAI.

Nitrogen application, planting density, and their interaction also significantly improved maize canopy structure. However, the present study found that plant height increased continuously from the seedling stage to the filling stage with increasing planting density and nitrogen application, although the magnitude of increase was limited. This indicates that increased planting density combined with nitrogen application improved the nutritional status of the maize population, but did not reduce plant height. This may be because plant height is regulated more strongly by genetic factors than by external agronomic practices, which is consistent with the findings of Zhang et al. [32].

The present study further showed that the D3 planting density adversely affected dry matter accumulation in maize from the jointing to tasseling stages. This effect may be attributed to alterations in canopy radiation distribution under high-density planting, which reduced light penetration into the lower canopy and consequently constrained assimilate production at the population level. Meanwhile, excessive nitrogen supply under the N3 treatment disrupted the nutrient balance of leaves, impaired photosynthetic efficiency, and accelerated non-productive nutrient consumption, thereby further restricting dry matter partitioning and accumulation [30]. At the same time, the N3 nitrogen level constrained photosynthesis and nutrient balance, ultimately resulting in reduced dry matter accumulation. This is similar to the findings of Han et al. [33], although some differences were observed in the magnitude of the effect on dry matter accumulation. These discrepancies may be attributed to multiple factors, including the regional environmental conditions and maize cultivar adopted in this experimental site. Therefore, planting density and nitrogen application can help establish a rational canopy structure and play an important role in yield improvement. However, in different agroecological regions, further exploration is still needed in combination with soil properties, climatic conditions, and other local factors.

4.2. Effects of Planting Density and Nitrogen Application on Maize Photosynthesis

Promoting leaf photosynthesis is the basis for improving crop productivity, and appropriate planting density and nitrogen application can improve the photosynthetic characteristics of the crop population [25,28]. Leaf SPAD values and Pn are key indicators of leaf photosynthetic capacity. Their levels directly determine the assimilate-supplying capacity of source leaves, thereby influencing dry matter accumulation and overall crop population productivity [34]. The present study showed that maize maintained a relatively high Pn from the seedling to the grain-filling stage under the D2 planting density, whereas excessive planting density (D3) significantly reduced leaf photosynthetic efficiency. These

findings indicate that once planting density exceeds a critical threshold, the uniformity of radiation distribution within the canopy is disrupted. Excessive canopy closure intensifies mutual shading among plants and substantially reduces light penetration to the middle and lower canopy layers, thereby markedly decreasing the net photosynthetic rate. In contrast, leaf SPAD values exhibited a pronounced stage-dependent response to planting density. Increasing planting density significantly enhanced leaf SPAD values at the seedling and jointing stages; however, under high-density conditions, SPAD values declined continuously from the booting to the grain-filling stage. This response may be attributed to the relatively compact canopy structure and weak interplant competition during the early growth stages, when moderate increases in planting density combined with nitrogen application synergistically promote chlorophyll synthesis and enhance leaf greenness. During the later growth stages, however, high planting density intensifies competition for soil nitrogen resources and aggravates canopy closure and shading aboveground, thereby disrupting chlorophyll metabolism, accelerating chlorophyll degradation, and ultimately leading to a significant decline in leaf SPAD values [35].

Nitrogen is an essential component of chlorophyll, proteins, nucleic acids, and other important substances in crops. Increased nitrogen application can promote chlorophyll synthesis in leaves and thus directly or indirectly affect photosynthesis. Similar results were found in the present study: nitrogen application increased both Pn and SPAD value in maize leaves. However, from the boot stage to the filling stage, leaf SPAD value and Pn under the D3N3 treatment declined. This indicates that nitrogen is also one of the factors limiting further improvement in photosynthetic efficiency, and excessive nitrogen application may suppress the enhancement of maize photosynthetic performance [33]. Therefore, increasing planting density and nitrogen application can both improve leaf SPAD value and Pn, but thresholds exist for both factors. Once these thresholds are exceeded, chlorophyll synthesis in leaves is inhibited, photosynthetic efficiency declines, and excessive nitrogen application may also cause soil pollution and environmental problems.

4.3. Effects of Planting Density and Nitrogen Application on Maize Yield and Water and Nitrogen Use Efficiency

Adequate dry matter production is the basis for ensuring maize yield, and yield improvement mainly depends on increased population dry matter accumulation [36]. Therefore, increasing planting density has become an effective approach for regulating maize yield. The present study showed that increasing planting density and nitrogen application improved cob traits in maize. Under the D1 density, increased nitrogen application enhanced kernel rows per cob, 100-kernel weight, and grain fraction. However, under higher planting densities, additional nitrogen application could not compensate for the negative effects of excessive density on yield. Excessive planting density disrupted radiation distribution within the canopy, reduced effective radiation interception by functional leaves, and impaired canopy-level photosynthetic efficiency. These effects further constrained post-anthesis grain-filling and dry matter translocation efficiency, ultimately reducing assimilate accumulation in the grains [37]. The contribution of nitrogen application to yield improvement was also limited. Excessive nitrogen application may accelerate leaf senescence, affect filling rate and dry matter partitioning, disrupt the source–sink balance, and ultimately lead to yield reduction [38].

The present study also found that increasing planting density and nitrogen application improved water use efficiency and partial factor productivity of nitrogen. Under the same planting density, increasing nitrogen application reduced partial factor productivity of nitrogen. Under the D2 and D3 densities, water use efficiency showed a parabolic response to increasing nitrogen rate, with the N3 treatment reducing water use efficiency. This result is similar to that reported by Lu et al. [39]. Under the same nitrogen level, the responses

of water use efficiency and partial factor productivity of nitrogen to increasing planting density were similar to those observed for nitrogen application. This may be because, under high-density planting, nitrogen application disrupted the coordination between individual plants and the crop population, and therefore failed to improve water use efficiency [40]. Meanwhile, under high-density planting, reducing nitrogen application may retain part of the percolated water in the shallow soil layer, thereby promoting maize utilization of both nitrogen and water [41]. Therefore, an appropriate planting density combined with reduced nitrogen application can improve water and nitrogen use efficiency in maize. This is generally consistent with the results of the present study, although the degree of water and nitrogen use efficiency may vary depending on crop cultivar, climatic conditions, and soil properties in different experimental regions.

5. Conclusions

This two-year field study provides evidence that coordinated regulation of planting density and nitrogen input is essential for reconciling canopy productivity, grain formation, and resource use efficiency in maize production under arid conditions. The results highlight an important threshold effect: moderate increases in planting density and nitrogen supply improved canopy structure and photosynthetic performance, whereas excessive inputs intensified canopy competition, restricted post-anthesis assimilate translocation to the grain, and reduced both water and nitrogen use efficiency. Thus, the scientific contribution of this study lies in demonstrating that yield improvement in arid maize systems depends not on maximizing either plant density or nitrogen input independently, but on optimizing their interaction to maintain a favorable canopy environment and source–sink balance. From a practical perspective, a planting density of 90,000 plants ha^{−1} combined with a nitrogen rate of 264 kg N ha^{−1} achieved the most favorable balance between grain yield and resource use efficiency under the conditions of this study. This combination therefore represents a promising management strategy for improving the productivity and sustainability of maize production in arid regions.

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Abbreviations

The following abbreviations are used in this manuscript:

SPAD	relative chlorophyll content
LAI	leaf area index
Pn	net photosynthetic rate
NPFP	nitrogen partial factor productivity
ET	evapotranspiration

References

1. Gao, J.; Dong, D.; Huang, W.; Dong, Y.; Xu, T.; Jiang, C.; Wang, K. Development and validation of a crop yield prediction framework accounting for regional heterogeneity: A case study of spring maize in Jilin Province. *Eur. J. Agron.* **2026**, *174*, 127977. [\[CrossRef\]](#)
2. Falcon, W.P.; Naylor, R.L.; Shankar, N.D. Rethinking global food demand for 2050. *Popul. Dev. Rev.* **2022**, *48*, 921–957. [\[CrossRef\]](#)
3. Teng, K.; Meng, S.; Liu, Y. Can alternating irrigation technology drive water saving in agricultural irrigation? Evidence from China. *Agric. Water Manag.* **2025**, *320*, 109867. [\[CrossRef\]](#)
4. Lu, H.; Huan, H. Does the transfer of agricultural labor reduce China's grain output? A substitution perspective of chemical fertilizer and agricultural machinery. *Front. Environ. Sci.* **2022**, *10*, 961648. [\[CrossRef\]](#)
5. Guo, J.; Qi, S.; Chen, J.; Lai, J. Driving Forces behind the Reduction in Cropland Area on Hainan Island, China: Implications for Sustainable Agricultural Development. *Land* **2024**, *13*, 1274. [\[CrossRef\]](#)
6. Begna, T.; Wakweya, R.B. Mitigating climate change impacts on food security via climate-smart agriculture. *Plant Stress* **2025**, *19*, 101152. [\[CrossRef\]](#)
7. Sheng, H.; Zhang, H.; Deng, H.; Zhang, Z.; Qiu, F.; Yang, F. Maize COMPACT PLANT 3 regulates plant architecture and facilitates high-density planting. *Plant Cell* **2025**, *37*, koaf029. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Duan, M.; Han, C.; Zhang, X.; Wei, Z.; Wang, Z.; Zhang, B. Spatial and Temporal Dynamics of Photosynthetically Active Radiation in Crops: Effects of Canopy Structure on Yield. *Agronomy* **2025**, *15*, 940. [\[CrossRef\]](#)
9. Ye, D.; Chen, J.; Yu, Z.; Gao, W.; Muneer, M.A.; Fan, K.; Wu, L.; Wu, H. Strategic cultivar and planting density integration: Optimizing canopy structure for enhanced yields in sweet maize. *Agron. J.* **2025**, *117*, e70052. [\[CrossRef\]](#)
10. Wei, L.C.; Zhang, H.P.; Wang, X.L.; Zhang, S.Q. Improved water use of the maize soil–root–shoot system under the integrated effects of organic manure and plant density. *Agronomy* **2023**, *13*, 1172. [\[CrossRef\]](#)
11. Lai, Z.; Kou, H.; Fan, J.; Yang, R.; Xu, X.; Zhang, F.; Li, S. Optimized planting density and nitrogen rate increased grain yield and water-nitrogen use efficiency of two maize cultivars under mulched drip fertigation by improving population photosynthesis and grain-filling characteristics. *Water* **2022**, *15*, 163. [\[CrossRef\]](#)
12. Ye, D.; Chen, J.; Yu, Z.; Sun, Y.; Gao, W.; Wang, X.; Zhang, R.; Zaib-Un-Nisa; Su, D.; Atif Muneer, M. Optimal plant density improves sweet maize fresh ear yield without compromising grain carbohydrate concentration. *Agronomy* **2023**, *13*, 2830. [\[CrossRef\]](#)
13. Li, H.; Wang, X.; Brooker, R.W.; Rengel, Z.; Zhang, F.; Davies, W.J.; Shen, J. Root competition resulting from spatial variation in nutrient distribution elicits decreasing maize yield at high planting density. *Plant Soil* **2019**, *439*, 219–232.
14. Wang, J.; Chen, Z.; Liang, Z.; Yin, Y.; Huang, S.; Meng, Q.; Cui, Z.; Wang, P. Interactive Effects of Planting Density and Row Spacing on Maize Root Distribution and Yield. *Agronomy* **2025**, *15*, 2552. [\[CrossRef\]](#)
15. Sciarresi, C.; Thies, A.; Topp, C.; Eudy, D.; Kovar, J.L.; Trifunovic, S.; Dixon, P.M.; Archontoulis, S.V. Breeding for high maize yields indirectly boosting root carbon in the US Corn Belt since the 1980s. *Field Crop. Res.* **2025**, *323*, 109774. [\[CrossRef\]](#)
16. Chang, H.; Chen, H.; Wang, J.; Wu, Q.; Deng, B.; Qin, Y.; Chen, S.; Liang, Q. Optimizing Planting Density and Nitrogen Application Enhances Root Lodging Resistance and Yield via Improved Post-Anthesis Light Distribution in Sweet Corn. *Plants* **2026**, *15*, 200. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Xue, J.; Gou, L.; Zhao, Y.; Yao, M.; Yao, H.; Tian, J.; Zhang, W. Effects of light intensity within the canopy on maize lodging. *Field Crop. Res.* **2016**, *188*, 133–141. [\[CrossRef\]](#)
18. Yan, Y.; Duan, F.; Li, X.; Zhao, R.; Hou, P.; Zhao, M.; Li, S.; Wang, Y.; Dai, T.; Zhou, W. Photosynthetic capacity and assimilate transport of the lower canopy influence maize yield under high planting density. *Plant Physiol.* **2024**, *195*, 2652–2667. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Liao, Z.; Jiang, X.; Pei, S.; Wu, Q.; Farooq, M.; Urano, D.; Seidel, S.J.; Li, Z.; Fan, J. Root-shoot synergy mediates resource utilization and grain yield of rainfed maize under nitrogen fertilization and soil mulching. *Agric. Water Manag.* **2025**, *322*, 110032. [\[CrossRef\]](#)

20. Zheng, Y.; Yue, Y.; Li, C.; Wang, Y.; Zhang, H.; Ren, H.; Gong, X.; Jiang, Y.; Qi, H. Revolutionizing maize crop productivity: The winning combination of zigzag planting and deep nitrogen fertilization for maximum yield through root–shoot ratio management. *Agronomy* **2023**, *13*, 1307. [\[CrossRef\]](#)
21. Liu, F.; Ning, X.; Yang, J.; Han, Z.; Ren, Y.; Wang, J.; Hu, H.; Zhou, Y.; Yin, X.; Sun, S.; et al. Coordinated nitrogen placement and rate optimization strengthen root–nitrogen coupling and improve nitrogen use efficiency in dryland maize. *Soil Tillage Res.* **2026**, *260*, 107146. [\[CrossRef\]](#)
22. Moises, C.; Andrade, F.H.; Monzon, J.P.; Calvo, N.I.R.; Cerrudo, A. Nitrogen deficiency in maize fields of the Southern Pampas does not affect kernel number but reduces weight per kernel. *Field Crop. Res.* **2024**, *312*, 109394. [\[CrossRef\]](#)
23. Lan, T.; Du, L.; Wang, X.; Zhan, X.; Liu, Q.; Wei, G.; Lyu, C.; Liu, F.; Gao, J.; Feng, D.; et al. Synergistic effects of planting density and nitrogen fertilization on chlorophyll degradation and leaf senescence after silking in maize. *Crop J.* **2024**, *12*, 605–613. [\[CrossRef\]](#)
24. Cheng, Y.; Chen, X.; Ren, H.; Zhang, J.; Zhao, B.; Ren, B.; Liu, P. Deep nitrogen fertilizer placement improves the yield of summer maize (*Zea mays* L.) by enhancing its photosynthetic performance after silking. *BMC Plant Biol.* **2025**, *25*, 172. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Ding, C.; Du, C.L.; Xie, H.J.; Meng, H.F.; Wang, L.L.; Zhou, Y.J.; Li, Z.K.; Li, L.L. Photosynthetic physiological mechanisms underlying improved grain yield and quality in dryland maize through nitrogen management. *Acta Agron. Sin.* **2025**, *51*, 3080–3095. (In Chinese) [\[CrossRef\]](#)
26. Liu, Z.; Zhou, W.; Wang, Z.; Zhao, Y.; Cheng, J.; Wang, X.; Zhou, B.; Ding, Z.; Mi, G.; Li, C. Quantifying contributions of efficiency-enhanced nitrogen fertilizers to maize production and environment: Evidence for sustainable agriculture policy framework. *Agric. Syst.* **2025**, *230*, 104488. [\[CrossRef\]](#)
27. Guo, J.G.; Jiang, X.F.; Xie, X.L.; Zheng, R.; Miao, C.Q.; Wei, J.R. Effect of Crop Planting Structure on Formation of Natal Host Types of *Helicoverpa armigera* Moths in Hexi Corridor. *Sci. Agric. Sin.* **2025**, *58*, 2782–2792. (In Chinese)
28. Sun, L.K.; Li, X.Y.; Guo, H.Z.; Yang, K.N.; Wang, C.Y.; Yao, X.Y.; Yang, X.J.; Xi, S.L.; Wei, Y.P.; Li, R.F.; et al. Effects of nitrogen application rate and planting density on light interception in different maize canopy layers, grain filling, and yield. *Trans. Chin. Soc. Agric. Eng.* **2025**, *41*, 101–113. (In Chinese)
29. Li, C.; Tong, B.; Jia, M.; Xu, H.; Wang, J.; Sun, Z. Integrated management strategies increased silage maize yield and quality with lower nitrogen losses in cold regions. *Front. Plant Sci.* **2024**, *15*, 1434926. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Lei, H.; Zhou, F.; Cai, Q.; Wang, X.; Du, L.; Lan, T.; Kong, F.; Yuan, J. Effects of planting density and nitrogen management on light and nitrogen resource utilization efficiency and yield of summer maize in the Sichuan hilly region. *Agronomy* **2024**, *14*, 1470. [\[CrossRef\]](#)
31. Duan, F.; Wei, Z.; Soualiou, S.; Zhou, W. Nitrogen partitioning in maize organs and underlined mechanisms from different plant density levels and N application rate in China. *Field Crop. Res.* **2023**, *294*, 108874. [\[CrossRef\]](#)
32. Zhang, X.; Akebot, M.; Yang, J.; Abulaiti, A.; Liang, X.L.; Lv, Y.P.; Han, D.X.; Li, M.D.; Dong, Y.; Qin, T.Y.; et al. Evaluation of density tolerance of the main maize varieties in Xinjiang China at 9.75 million plants/hm² and 12.00 million plants/hm² densities. *J. Maize Sci.* **2025**, 1–13. Available online: <https://link.cnki.net/urlid/22.1201.s.20250422.1819.002> (accessed on 20 July 2026).
33. Han, X.; Xiao, X.; Zhang, J.; Shao, M.; Jie, Y.; Xing, H. Effects of nitrogen fertilizer and planting density on growth, nutrient characteristics, and chlorophyll fluorescence in silage maize. *Agronomy* **2024**, *14*, 1352. [\[CrossRef\]](#)
34. Ju, Z.; Liu, K.; Zhao, G.; Ma, X.; Jia, Z. Nitrogen fertilizer and sowing density affect flag leaf photosynthetic characteristics, grain yield, and yield components of oat in a semiarid region of northwest China. *Agronomy* **2022**, *12*, 2108. [\[CrossRef\]](#)
35. Guo, Y.; Wang, G.; Zhang, Z.; Guo, X.; Li, T.; Wang, Q.; Wei, J.; Li, P.; Chen, H.; Abdalla, M.; et al. Boosting maize yield under water reduction: Synergistic effects of increased planting density and sustained nitrogen input on photo–physiological characteristics. *J. Agric. Food Res.* **2025**, *24*, 102461. [\[CrossRef\]](#)
36. Liu, G.-Z.; Liu, W.-M.; Hou, P.; Ming, B.; Yang, Y.S.; Guo, X.X.; Xie, R.Z.; Wang, K.R.; Li, S.K. Reducing maize yield gap by matching plant density and solar radiation. *J. Integr. Agric.* **2021**, *20*, 363–370. [\[CrossRef\]](#)
37. Agackesen, M.; Oktem, A.; Oktem, A. Effect of harvest at different maturation stages on fresh ear yield and ear characteristics of sweet corn (*Zea mays* L. *saccharata*) genotypes. *Appl. Ecol. Environ. Res.* **2022**, *20*, 3335–3351. [\[CrossRef\]](#)
38. Du, K.; Zhao, W.; Lv, Z.; Xu, B.; Hu, W.; Zhou, Z.; Wang, Y. Optimal rate of nitrogen fertilizer improves maize grain yield by delaying the senescence of ear leaves and thereby altering their nitrogen remobilization. *Field Crop. Res.* **2024**, *310*, 109359. [\[CrossRef\]](#)
39. Lu, Y.; Ma, R.; Gao, W.; You, Y.; Jiang, C.; Zhang, Z.; Kamran, M.; Yang, X. Optimizing the nitrogen application rate and planting density to improve dry matter yield, water productivity and N-use efficiency of forage maize in a rainfed region. *Agric. Water Manag.* **2024**, *305*, 109125. [\[CrossRef\]](#)

40. Guo, R.; Qian, R.; Yang, L.; Khaliq, A.; Han, F.; Hussain, S.; Zhang, P.; Cai, T.; Jia, Z.; Chen, X.; et al. Interactive effects of maize straw-derived biochar and n fertilization on soil bulk density and porosity, maize productivity and nitrogen use efficiency in arid areas. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 4566–4586. [[CrossRef](#)]
41. Bai, T.; Wang, P.; Ye, C.; Hu, S. Form of nitrogen input dominates N effects on root growth and soil aggregation: A meta-analysis. *Soil Biol. Biochem.* **2021**, *157*, 108251. [[CrossRef](#)]

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