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Optimum Plant Density Improved Cotton (*Gossypium hirsutum* L.) Root Production Capacity and Photosynthesis for High Cotton Yield under Plastic Film Mulching

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Abstract: Cotton photosynthetic efficiency and the root–shoot relationship are two important physiological indexes affecting the final yield, but the interactive effects of plastic film mulching and planting density on the cotton photosynthetic efficiency and root–shoot relationship have rarely been reported. We aimed to investigate the optimal plant density with or without plastic film mulching for improved seed cotton yield in southern Xinjiang. Therefore, a two-year field experiment was conducted to investigate the effects of plastic film mulching (with or without plastic film mulching) and planting density (D1: 9×10^4 plants ha^{-1}; D2: 18×10^4 plants ha^{-1}; D3, 22×10^4 plants ha^{-1}, local conventional planting density; D4, 27×10^4 plants ha^{-1}) on the cotton root–shoot relationship, photosynthetic parameters, and seed cotton yield. Our results showed that the seed cotton yield was improved under plastic film mulching at all planting densities, but economic income was significantly lower in comparison to without plastic film mulching in 2023. Compared with D3, seed cotton yield and economic income at D2 increased by 6.9% and 12.2%, either with or without plastic film mulching, respectively. The highest increase in the seed cotton yield in D2 under plastic film mulching was due to the greatest improvements in the root production capacity and photosynthesis. The boll capacity of the root system (BCR) and boll loading of the root system (BLR) in D2 were the highest among all treatments with film mulching, being 9.0% and 16.9% higher than that in D3 in 2022 and 2023. However, the root–shoot ratio (R/S) was 7.1% and 6.9% lower in D2 than D3, under film mulching, in 2022 and 2023. Moreover, moderate plant density (D2) improved the SPAD value, chlorophyll fluorescence (F_v/F_m and PI_{abs}), and photosynthetic parameter (Pn, Tr, and Gs) and decreased Ci compared with other planting density treatments in both years. Further analyses with correlation analysis showed that the seed cotton yield was highly positive correlated with BLR, BCR, and the photosynthetic parameter. In summary, suitable planting density (18×10^4 plants ha^{-1}) combined with plastic film mulching has the potential to obtain high yields by enhancing the efficiency of photosynthetic assimilates, improving the capacity of cotton root production, providing a reference for suitable planting density under plastic film mulching.

Keywords: cotton (*Gossypium hirsutum* L.); film mulching; planting density; photosynthesis; root production capacity; seed cotton yield

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1. Introduction

Cotton (*Gossypium hirsutum* L.) has an extremely critical position in China's national economy and is regarded as a strategic material that affects both the country's economy and the livelihoods of its citizens. Xinjiang is a major cotton-producing region in China, accounting for over 90% of the country's cotton production in 2023 [1]. At present, Xinjiang's cotton industry still faces many problems, such as agricultural water shortages, expensive inputs, and several management and material inputs, that threaten cotton production [2]. Drip irrigation under mulch technology has made an important contribution to improving Xinjiang's cotton production [3]. And plant density is another useful agronomic technique for managing cotton populations and individual growth [4]. However, the optimal cotton density under film mulching is not completely understood.

Light spectrum variations, biomass distribution, root production, and leaf photosynthetic rate can all be significantly impacted by changes in planting density [4–6]. Planting density can impact crop competition for light and other resources. For example, high planting density (9×10^4 plant ha^{-1}) dramatically diminishes the structural and functional properties of cotton leaves, which reduces the ability of the leaf to compete for light and nutrients, ultimately resulting in a low photosynthetic rate [5]. In addition, the boll load was restricted by the decline in leaf photosynthetic capability brought on by intense competition and the decrease in the chlorophyll fluorescence parameter under high planting density [7,8]. At high plant density, maize allocated substantially fewer photosynthates to the root, according to Shao et al. [9].

Crop yield and photosynthesis were directly correlated with the root–shoot relationship (R/S). To a certain extent, there was a substantial positive correlation between root development and yield formation; nevertheless, excessive root biomass can reduce the yield by consuming too much photosynthetic material provided by the shoots [10,11]. Hossain et al. [12] pointed out that crops were more inclined to reduce the root–shoot ratio and then used more assimilates to promote photosynthesis efficiency when soil nutrients were adequate. Planting density has an impact on crop root systems, as numerous earlier studies have demonstrated [13,14]. Few studies, nevertheless, have examined the connections between photosynthetic factors and the cotton root–shoot relationship at various plant densities when using plastic film mulching. Furthermore, the root–shoot relationship was intimately related to the coordination of both vegetative and reproductive growth, in addition to influencing the efficiency of photosynthesis [11,15]. Boll capacity of the root system (BCR) and the boll loading of the root system (BLR) may serve as indicators of the coordination between vegetative and reproductive growth [16]. According to Wang et al. [17], mulched drip irrigation, as opposed to typical irrigation, reduced the R/S of cotton and increased the BLR at the boll opening stage by giving cotton bolls more photosynthates, hence avoiding the energy consumption of redundant root growth. It has been established that cotton's BCR and BLR may be readily increased through cultivation methods, and this improvement was favorably connected with the seed cotton yield [11,15]. However, the effects of planting density and plastic film mulching on the relationship between R/S, BCR, BLR, and seed cotton yield in Xinjiang are unclear.

Planting density determines the population number, and a reasonable population structure can be built to reduce conflict between the population and individuals and maximize crop output in a cropping system [18]. Cotton at high density (>10 plants m^{-2}) may result in an infestation of diseases, smaller bolls, fruit shedding, delayed maturity, and poorer development of individual plants [19,20]. Dong et al. [7] also reported that boll weight and boll number had a trend toward decreases when increasing the plant density. A study by Guzman et al. [21] indicated that the highest lint yields can be achieved with planting densities between 83,333 and 100,000 plant ha^{-1} based on the varieties employed in Venezuela's savannahs. Appropriate planting density could build a good population structure and improve light energy utilization, both of which have an impact on population growth and production [22]. Prior research has examined the impact of varying planting densities on cotton growth in various conditions, such as different sowing dates or nitrogen supply [7,14,23]. However, the effect of planting densities on cotton growth and yield, without and with plastic film mulching, has not yet been documented. Also, plastic mulch is widely used in Xinjiang, but high input costs coupled with multiple management and material inputs endanger cotton productivity in Xinjiang [2]. In addition to optimizing production and photosynthesis, a suitable plant density can reduce inputs by requiring fewer seeds without sacrificing the yield [24]. Thus, it is necessary to explore an economical and green agricultural cotton production system characterized by moderate planting density, with or without plastic film mulching.

The effects of varying planting densities and film mulching on leaf photosynthetic metrics, as well as the relationship between root–shoot and seed cotton yield, are investigated in this study. We also investigated the optimal plant density with or without plastic film mulching for improved seed cotton yield in Xinjiang. Our hypothesis was that a moderate planting density would enhance the capacity of cotton leaves to photosynthesize and the capacity of root production, as well as the ability of assimilate transport to cotton bolls, all of which would lead to an increase in seed cotton yield. These results will help with the sustainable development of cotton in southern Xinjiang.

2. Materials and Methods

2.1. Details of Experimental Site

The field trial was conducted at Alar (40°32′ N, 81°18′ E), Xinjiang, China, from 2022 to 2023. This region is a typical warm temperate continental arid desert climate, with an altitude of 1015 m. During the cotton growing season (April–October) in 2022 and 2023, the daily average temperature was 23.1 °C and 22.6 °C; the total precipitation was 16.2 mm and 32.0 mm, respectively (Figure 1). It is worth pointing out that the mean and minimum air temperature during the cotton emergence period (late-April) was lower in 2023 than that in 2022. And this region faced rain for a few days during the cotton boll opening period (late September) in 2023. The soil type was sandy loam with a pH of 7.93, contained 10.59 g kg^{-1} of organic matter, and 1.72 mg kg^{-1}, 162.31 mg kg^{-1}, and 29.66 mg kg^{-1} of available nitrogen, potassium, and phosphorus, respectively, at the initiation of the experiment.

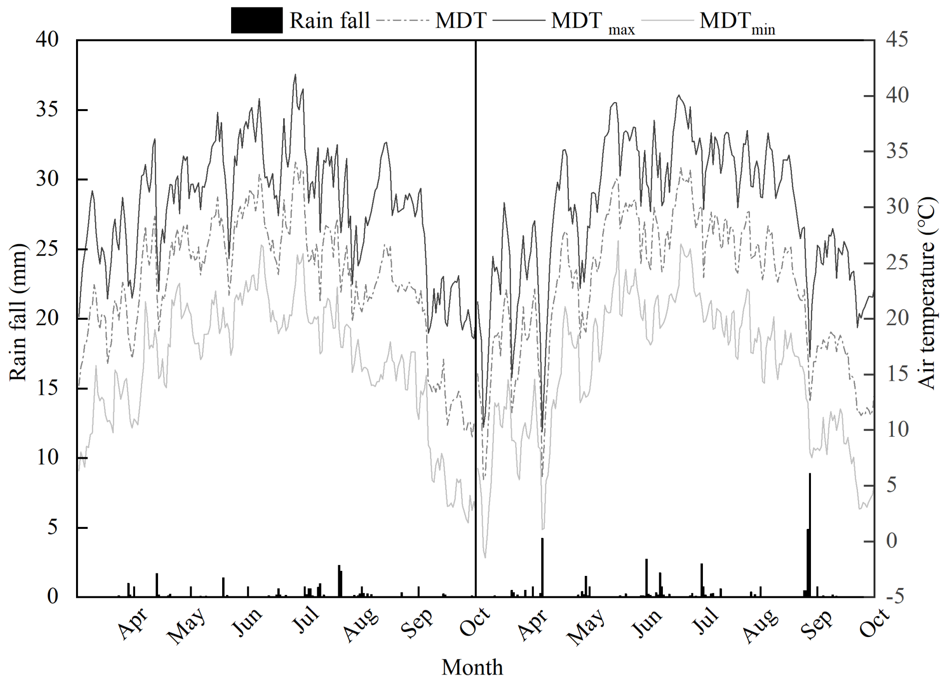

Figure 1. Daily mean air temperature (MDT), daily maximum air temperature (MDT_{max}), daily minimum air temperature (MDT_{min}), and daily precipitation during cotton growing period (April–October) from 2022 to 2023.

2.2. Experimental Design

This experiment was conducted using a two-factor split-plot design with four replications. The main plot was two different planted pattern treatments (FM, film mulching; NM, no mulching), and the subplot was four planting density treatments (D1, 9×10^4 plants ha^{-1}; D2, 18×10^4 plants ha^{-1}; D3, 22×10^4 plants ha^{-1}, local conventional planting density; D4, 27×10^4 plants ha^{-1}). Each subplot size was 11.5 m^2 (5 m × 2.3 m). The cotton cultivar "zhongmian 619" was sown in mid-April in both years (2022 and 2023). Fertilizer was applied with water at each irrigation, with the amount of nitrogen fertilizer at 315 kg ha^{-1} (urea, 46.4% N), phosphorus fertilizer at 198 kg ha^{-1} (diammonium phosphate, 46% P_2O_5), and potassium fertilizer at 79.2 kg ha^{-1} (50% K_2O). All the other necessary field management practices, such as irrigation, weed, plant pruning, and insect control, were implemented in accordance with local high-yield cultivation management measures.

2.3. Plant Sampling and Analysis

At the cotton boll opening stage in 2022 and 2023, five representative cotton plant samples were manually collected from each subplot. All of the plant samples from the same subplot were combined as a composite sample. The plant sample was partitioned into different organs (root, stem, leaf, and boll), and the number of bolls per plant was recorded. The plant organ sample was dried at 105 °C for 30 min and then oven-dried at 80 °C to constant weight; they were finally weighed to calculate the different organ biomasses.

The boll capacity of the root system (BCR) and the boll loading of the root system (BLR) represent the productive capacity of the root biomass. The BCR and BLR were calculated as shown in following equation according to [16]:

$$\text{BCR}(\text{g g}^{-1}) = \text{Boll biomass}(\text{g plant}^{-1})/\text{Root biomass}(\text{g plant}^{-1}) \quad (1)$$

$$\text{BLR}(\text{no g}^{-1}) = \text{Boll number }(\text{no plant}^{-1})/\text{Root biomass}(\text{g plant}^{-1}) \quad (2)$$

The root–shoot ratio (R/S) was calculated as follows:

$$\text{R/S} = \text{Root biomass}(\text{g plant}^{-1})/\text{Shoot biomass}(\text{g plant}^{-1}) \quad (3)$$

2.4. Determination of SPAD Value, Chlorophyll Fluorescence Traits, and Photosynthetic Characteristics

For each subplot, ten young cotton leaves were selected to determine SPAD value using a SPAD-502plus (Konica Minolta, Tokyo, Japan) chlorophyll meter. The fully expanded leaves on main stem were selected to measure photosynthetic performance index (PI_{abs}) and maximal quantum efficiency (F_v/F_m) after 30 min of dark adaption using Handy PEA fluorometer (Hansatech, Kings Lynn, UK). Three fully expanded functional leaves of the main stem were taken from different cotton plants, and the net photosynthetic rate (Pn), stomatal conductance (GS), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) were determined using a Li-Cor6400 photosynthesizer (LI-COR, Lincoln, NE, USA) equipped with fluorescent leaf chambers (Li6400-40) between 12:00 and 14:00 on a sunny day. The air flow rate was set at 500 μmol m^{-2} s^{-1}, the CO_2 concentration at 400 μmol mol^{-1}, the air relative humidity in the leaf chamber was controlled at 60–70%, and the artificial light source was set to 1500 μmol m^{-2} s^{-1}.

2.5. Seed cotton Yield and Economic Income

At the cotton boll opening stage, two central rows in each subplot of cotton plants were manually collected to determine seed cotton yield in 2022 and 2023. To assess economic income, film input and film residual fees for physical inputs were considered, as well as other inputs consistent with or without plastic film mulching. Input costs were calculated based on the local material prices, and the seed cotton yield output was calculated based on the average market price in 2022 and 2023.

2.6. Data Analysis

A two-way analysis of variance (ANOVA) was implemented to measure the effects of plastic film mulching and planting density on BCR, BLR, R/S, SPAD value, chlorophyll fluorescence parameters, photosynthetic parameters, seed cotton yield, and economic income. The ANOVA and Pearson's correlation analysis were processed using IBM SPSS Statistics 26 software. Statistical differences among treatments were performed using the least significant difference (LSD) test at $p < 0.05$ probability level. Relationships between seed cotton yield and economic income were analyzed by Origin 2022 using a second-order polynomial model. Origin 2022 (OriginLab, Hampden, MA, USA) was used to create figures.

3. Results

3.1. BCR, BLR, and R/S

Plastic film mulching and planting density had obvious effects on the boll capacity of the root system (BCR) and the boll loading of the root system (BLR) (Figure 2). Compared with no mulch, plastic film mulching significantly increased the cotton BCR and BLR by 7.3–43.8% and 18.5–23.6% across all plant densities in average growing seasons. BCR and BLR showed an increased and then decreased trend as the density increased; the value peaked in D2, with both plastic film mulching and no mulching. Compared with D3, BCR and BLR at D2 increased by 12.5% (FM) and 4.1% (NM), and 7.1% (FM) and 5.9% (NM), on average, across years, respectively. Under film mulching, the BCR in D1 was higher than that in D3 and D4, and the BLR in D3 was higher than that in D1 and D4.

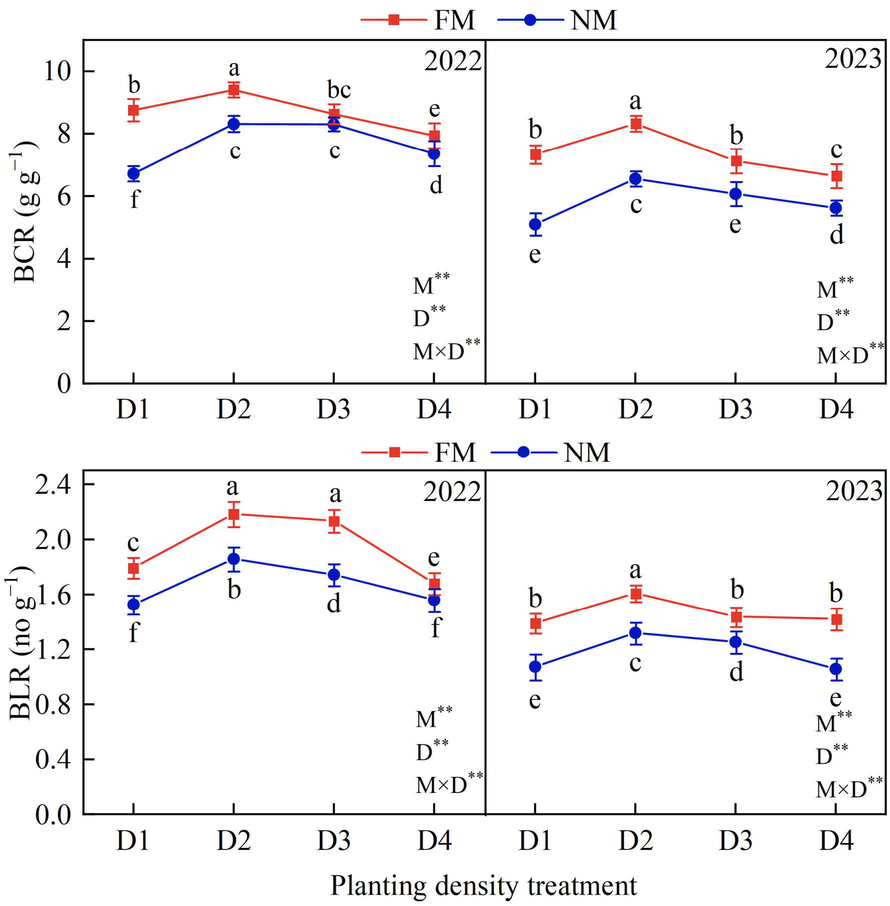

Figure 2. Effects of plastic film mulching (M) and planting density (D) on cotton boll capacity of the root system (BCR) and boll loading of the root system (BLR) at boll opening stage. FM, film mulching; NM, no mulching. D1, 9 × 10^4 plants ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). ** represent significant differences at $p < 0.01$ probability level. Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

Two-way ANOVAs indicated plastic film mulching and planting density had significant effects on the root–shoot ratio (R/S), as well as their interactions in 2022 and 2023 (Figure 3). The plastic film significantly decreased the cotton R/S by 10.5–21.7% and 6.5–19.0% across all plant densities in average growing seasons, relative to no mulching. Cotton R/S increased with the increasing planting density in film mulching and no mulching treatment. The R/S in D2 decreased by 5.8% (FM) and 9.6% (NM), and 19.1% (FM) and 11.2% (NM), averaged across years compared to D3 and D4, respectively.

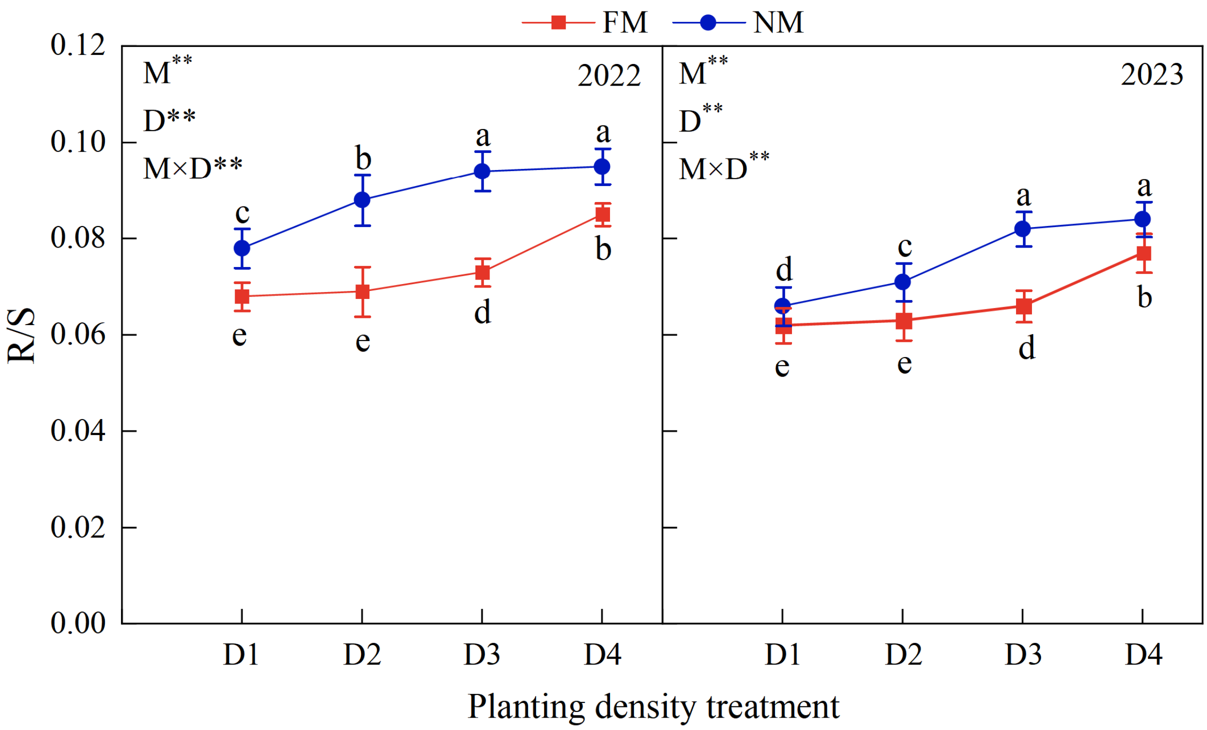

Figure 3. Effects of plastic film mulching (M) and planting density (D) on cotton R/S. FM, film mulching; NM, no mulching. D1, 9 × 10^4 plants ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). ** represent significant differences at $p < 0.01$ probability level. Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

3.2. Cotton Biomass

Cotton biomass was tested at the boll opening stage (Figure 4). Analysis of two-way ANOVAs indicated plastic film mulching and planting density had significant effects on cotton biomass, as well as their interactions in 2022 and 2023. Compared with no mulch, plastic film mulching significantly increased the cotton biomass by 16.8–36.0% across all plant densities over an average of two years. The planting density of cotton also had a significant influence on cotton biomass. Cotton biomass tended to first increase, then decrease as the density increased, and the value peaked in D2 plastic film mulching and no mulching. The cotton biomass in D2 was 18.2% (FM), 29.0% (NM), 8.1% (FM), 10.5% (NM), 24.9% (FM), and 43.0% (NM) higher than that in D1, D3, and D4, on average, in the growth stages in both years, respectively.

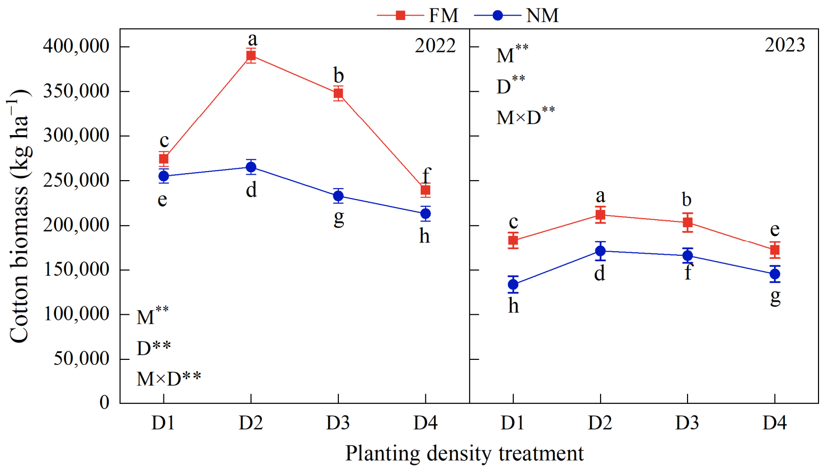

Figure 4. Effects of plastic film mulching (M) and planting density (D) on cotton biomass at boll opening stage. FM, film mulching; NM, no mulching. D1, 9 × 10^4 plants ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). ** represent significant differences at $p < 0.01$ probability level. Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

3.3. SPAD Value

Compared with no mulch, plastic film mulching significantly increased the cotton SPAD value by 3.7–16.7% at the peak squaring stage; 1.7–6.5% at the peak flowering stage; 0.6–6.0% at the peak boll-setting stage; 3.4–11.1% at the boll opening stage (under various plant densities across the years) (Figure 5). The SPAD value tended to first increase, then decrease as the density increased, and the value peaked in D2 plastic film mulching and no mulching under varied growth stages in both years. Compared with D2, the cotton SPAD value decreased by 6.0–9.4% (FM) and 4.8–10.2% (NM) under D1, decreased by 4.6–7.0% (FM) and 5.1–9.9% (NM) under D3, and decreased by 8.3–9.2% (FM) and 5.8–12.4% (NM) under D4, on average, in the growth stages in both years, respectively.

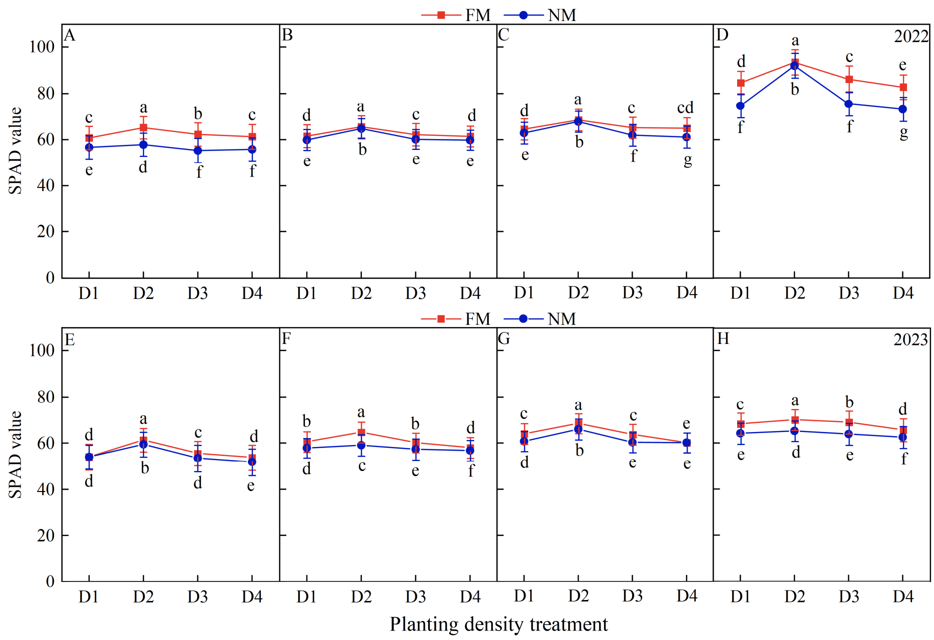

Figure 5. Changes of SPAD value at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and 2023 with (FM) or without (NM)

plastic film mulching under different planting density. D1, 9 × 10^4 plants ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

3.4. Chlorophyll Fluorescence Parameters

With the advancement of the growth process, the maximal quantum efficiency (F_v/F_m) and photosynthetic performance index (PI_{abs}) showed a trend of first increasing and then decreasing (Figures 6 and 7).

Compared with no mulch, plastic film mulching significantly increased the cotton F_v/F_m and PI_{abs} at the peak squaring stage, peak flowering stage, and peak boll-setting stage, but the F_v/F_m and PI_{abs} were lower under plastic film mulching than no mulch at the boll opening stage. F_v/F_m and PI_{abs} tended to first increase, then decrease as the density increased, and the value peaked in D2 plastic film mulching and no mulching under varied growth stages in both years. The F_v/F_m and PI_{abs} in D2 were 6.8–42.7% (FM), 4.6–45.2% (NM), 10.6–66.5% (FM), 10.1–29.1% (NM), 6.3–21.7% (FM), 6.5–20.6% (NM) and 29.2–34.0% (FM), 22.6–45.2% (NM), 8.7–27.5% (FM), 9.0–34.0% (NM), 36.0–50.5% (FM), and 34.3–47.7% (NM) higher than that in D1, D3, and D4, on average, in the growing stages in two years, respectively.

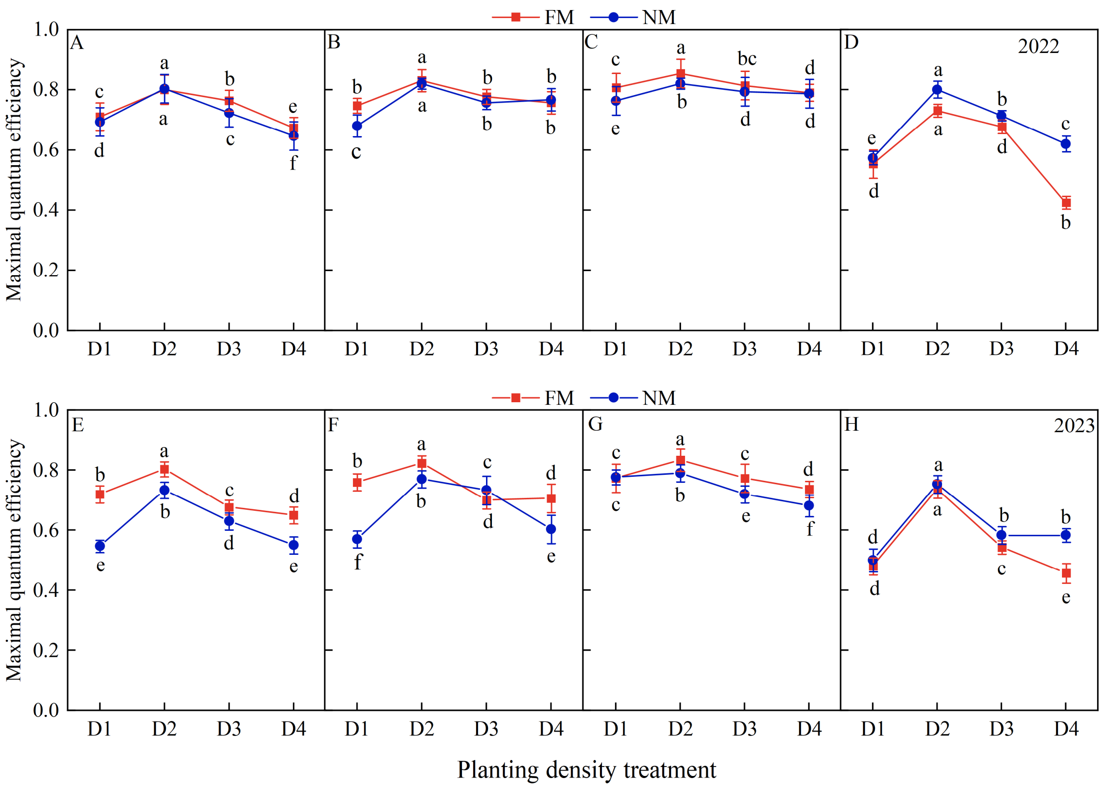

Figure 6. Changes of maximal quantum efficiency (F_v/F_m) at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and 2023 with (FM) or without (NM) plastic film mulching under different planting density. D1, 9 × 10^4 plants ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

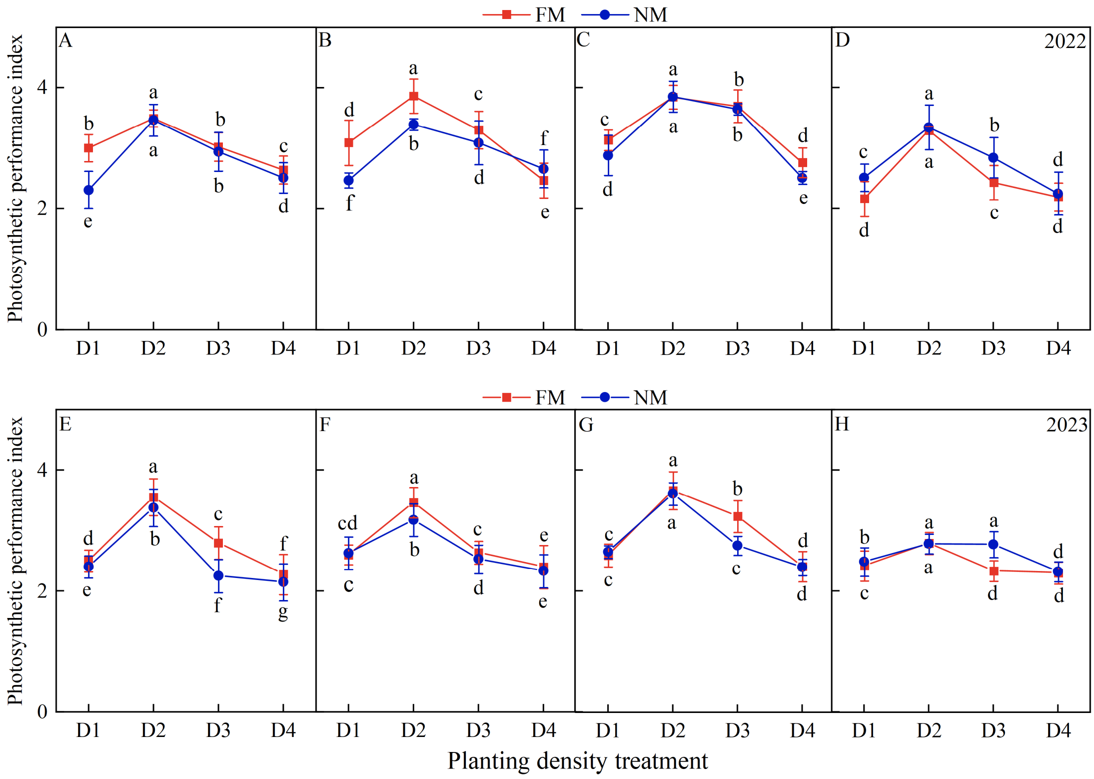

Figure 7. Changes of photosynthetic performance index (PI_{abs}) at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and 2023 with (FM) or without (NM) plastic film mulching under different planting density. D1, 9×10^4 plants ha^{-1}; D2, 18×10^4 plants ha^{-1}; D3, 22×10^4 plants ha^{-1}, local conventional planting density; D4, 27×10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

3.5. Photosynthetic Characteristics

The Pn, Tr, Gs, and Ci change trends with the growth and development process were the same as PI_{abs} and F_v/F_m. Compared with no mulch, plastic film mulching significantly increased Pn, Tr, Gs, and Ci at the peak squaring stage, peak flowering stage, and peak boll-setting stage; it was the opposite at the boll opening stage (Figures 8–11). Planting density had significant impacts on Pn, Tr, and Gs. The Pn, Tr, and Gs tended to first increase, then decrease as the density increased, and the value peaked in D2 plastic film mulching and no mulching under varied growth stages in both years. However, the Ci was first decreased and then increased with increasing planting density, and the Ci was the smallest in D2 (Figure 2). The Ci in D2 was 6.6–34.6% (FM), 8.3–39.2% (NM), 5.1–43.8% (FM), 4.2–45.4% (NM), 7.6–44.8% (PM), and 9.5–47.7% (NM) lower than that in D1, D3, and D4 on average for the growth stages in both years, respectively.

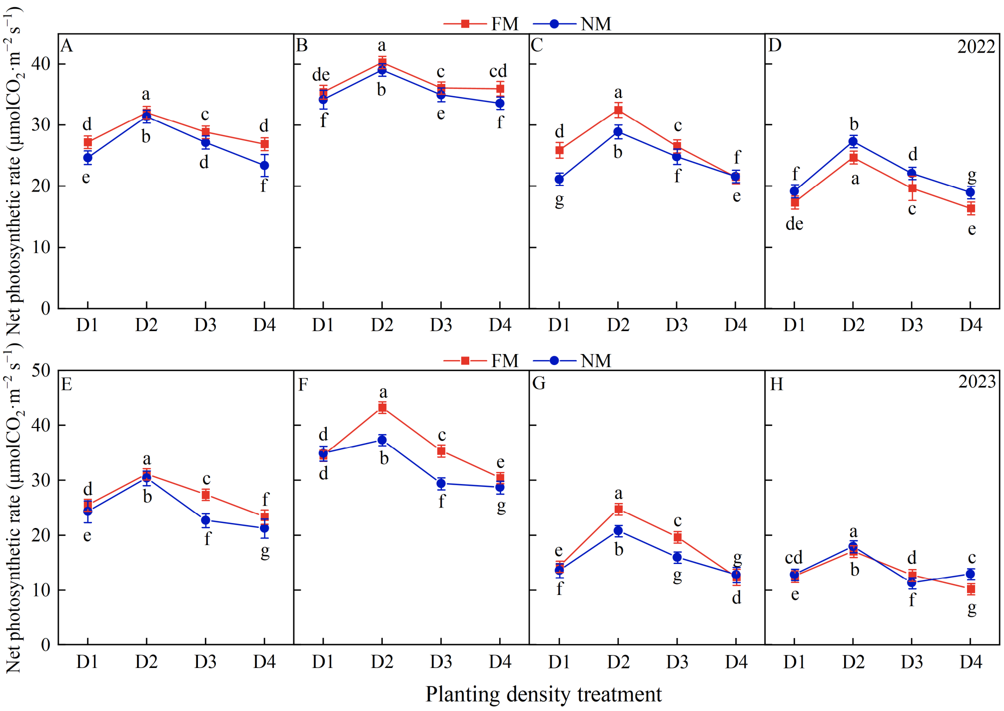

Figure 8. Changes of net photosynthetic rate (Pn) (μmol CO_2 m^{-2} s^{-1}) at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and 2023 with (FM) or without (NM) plastic film mulching under different planting density. D1, 9×10^4 plants ha^{-1}; D2, 18×10^4 plants ha^{-1}; D3, 22×10^4 plants ha^{-1}, local conventional planting density; D4, 27×10^4 plants ha^{-1}. Vertical bars indicate standard error ($n = 4$). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

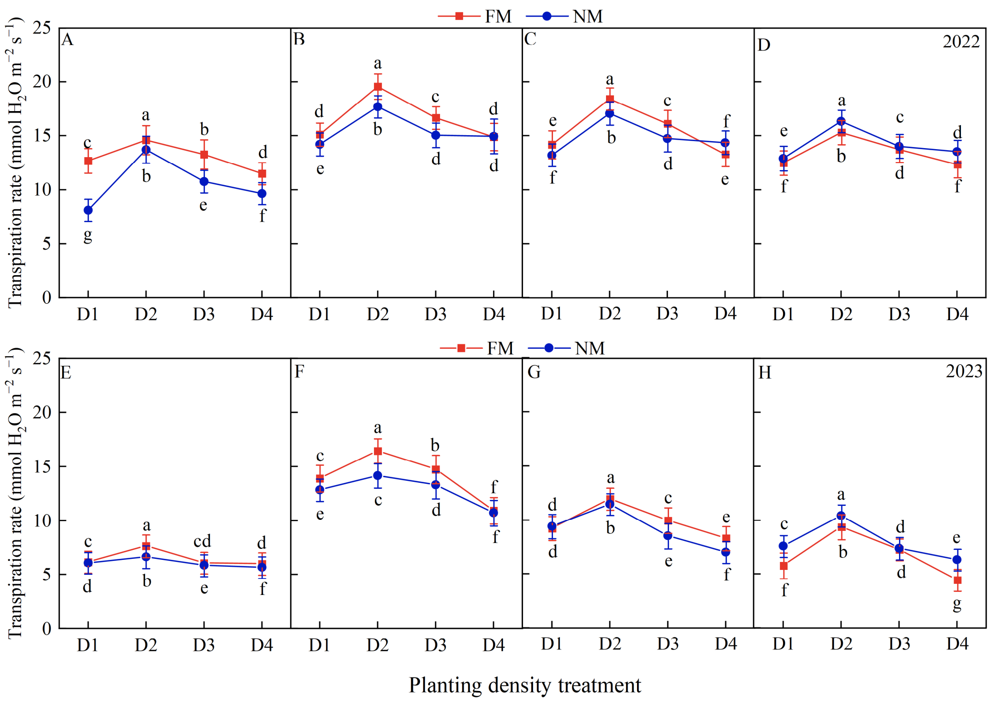

Figure 9. Changes of transpiration rate (Tr) (mmol H_2O m^{-2} s^{-1}) at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and 2023 with (FM) or without (NM) plastic film mulching under different planting density. D1, 9×10^4 plants

ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (*n* = 4). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

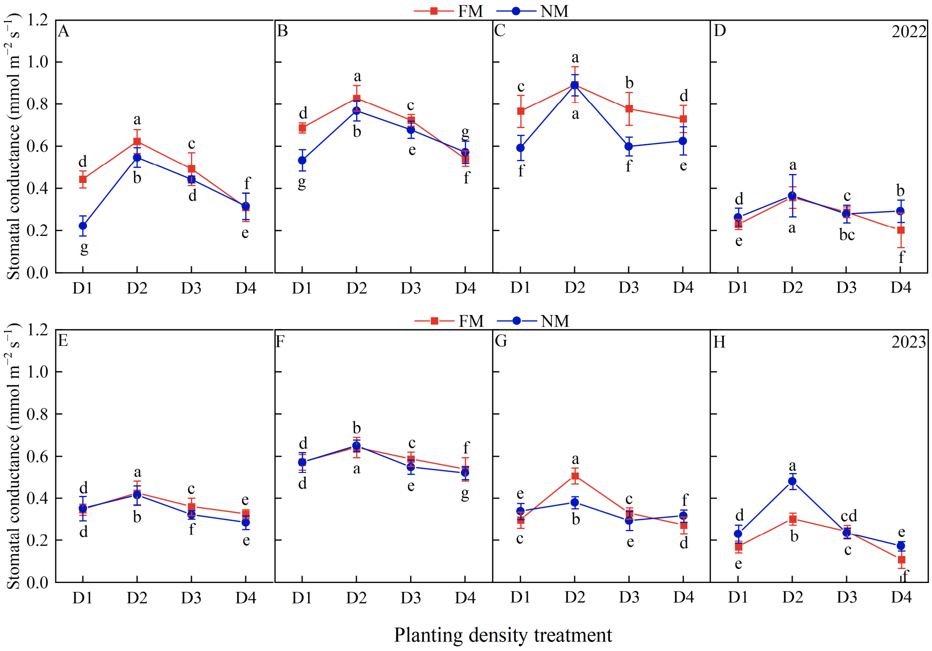

Figure 10. Changes of stomatal conductance (Gs) (mmol m^{-2} s^{-1}) at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and 2023 with (FM) or without (NM) plastic film mulching under different planting density. D1, 9 × 10^4 plants ha^{-1}; D2, 18 × 10^4 plants ha^{-1}; D3, 22 × 10^4 plants ha^{-1}, local conventional planting density; D4, 27 × 10^4 plants ha^{-1}. Vertical bars indicate standard error (*n* = 4). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

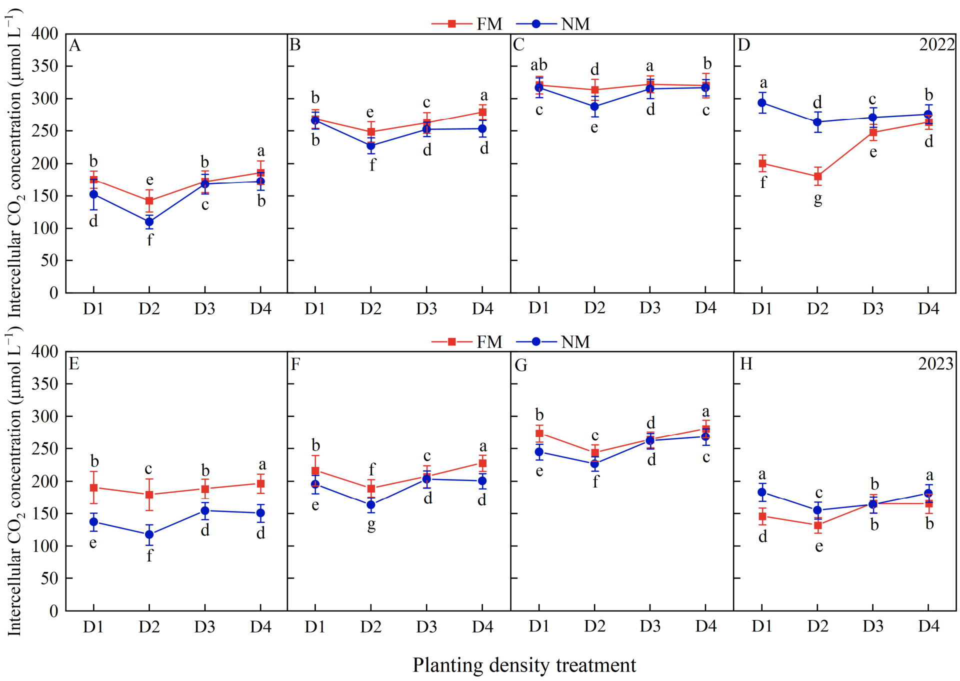

Figure 11. Changes of intercellular CO_2 concentration (Ci) (μmol L^{-1}) at peak squaring stage (**A**,**B**), peak flowering stage (**C**,**D**), peak boll-setting stage (**E**,**F**), and boll opening stage (**G**,**H**) in 2022 and

2023 with (FM) or without (NM) plastic film mulching under different planting density. D1, 9×10^4 plants ha^{-1}; D2, 18×10^4 plants ha^{-1}; D3, 22×10^4 plants ha^{-1}, local conventional planting density; D4, 27×10^4 plants ha^{-1}. Vertical bars indicate standard error (n = 4). Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

3.6. Yield, Economic Income, and Correlation

The analysis revealed that the seed cotton yield was significantly impacted by plastic film mulching and planting density, but their interactions were not significant (Table 1 and Figure 12). Plastic film mulching significantly increased the seed cotton yield by 6.8–10.4% and 1.6–10.1% across all planting densities in 2022 and 2023, relative to no mulching. The economic income in 2023 was significantly lower with plastic film mulching than that with no mulching. D2 treatment had the highest value on the seed cotton yield and economic income with both film mulching and no mulching. Compared with D3, the seed cotton yield and economic income at D2 increased by 6.7% (FM), 12.1% (NM), 7.0% (FM), and 12.2% (NM) in 2022 and 2023. Compared with no mulching, the economic income in D1, D2, and D3 were 3.4%, 4.3%, and 1.0% lower than that under plastic film mulching, respectively, in 2023; however, statistical differences were not found under film mulching and no mulching in 2022.

Table 1. Effects of plastic film mulching (M) and planting density (D) on seed cotton yield and economic income. FM, film mulching; NM, no mulching. D1, 9×10^4 plants ha^{-1}; D2, 18×10^4 plants ha^{-1}; D3, 22×10^4 plants ha^{-1}, local conventional planting density; D4, 27×10^4 plants ha^{-1}.

Mulch Treatments	Density	Yield		Economic Income	
		2022 (kg ha^{-1})	2023 (kg ha^{-1})	2022 (RMB ha^{-1})	2023 (RMB ha^{-1})
FM	D1	5309.57 b	4798.55 d	36,793.39 c	32,431.57 d
	D2	5805.07 a	5242.32 a	40,336.27 a	35,626.70 b
	D3	5384.06 b	4961.28 c	37,326.01 bc	33,603.18 c
	D4	5210.14 b	4657.97 e	36,082.54 cd	31,419.39 e
NM	D1	4810.14 c	4657.97 e	34,392.50 d	33,537.39 c
	D2	5436.96 b	5159.42 b	38,874.24 ab	37,147.83 a
	D3	4950.72 c	4504.35 f	35,397.68 cd	32,431.30 d
	D4	4846.38 c	4408.70 g	34,651.59 d	31,742.61 e
Analysis of variance					
M		**	**	*	**
D		**	*	**	**
M × D		ns	ns	ns	**

Note: *, **, and ns represent significant differences at $p < 0.05$, $p < 0.01$ probability level, and not significant, respectively. Treatments not sharing a common letter are significantly different at $p < 0.05$ by ANOVA and least significant difference test.

The F_v/F_m showed a strong significantly positive correlation with PI_{abs}, Pn, Tr, Gs, and seed cotton yield across all cotton growing stages (Figure 13). The seed cotton yield was positively related to BLR, BCR, Pn, and Tr. Additionally, cotton R/S and Ci were negatively related to the seed cotton yield.

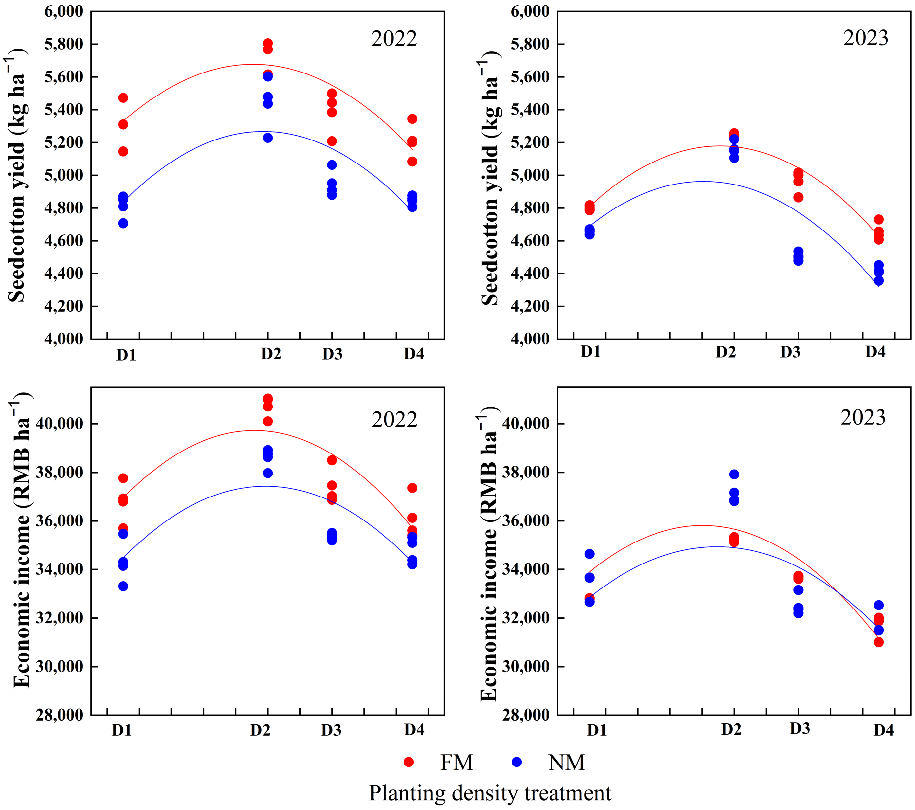

Figure 12. Responses of the seed cotton yield and economic income to the different planting densities with (FM) and without (NM) plastic film mulching.

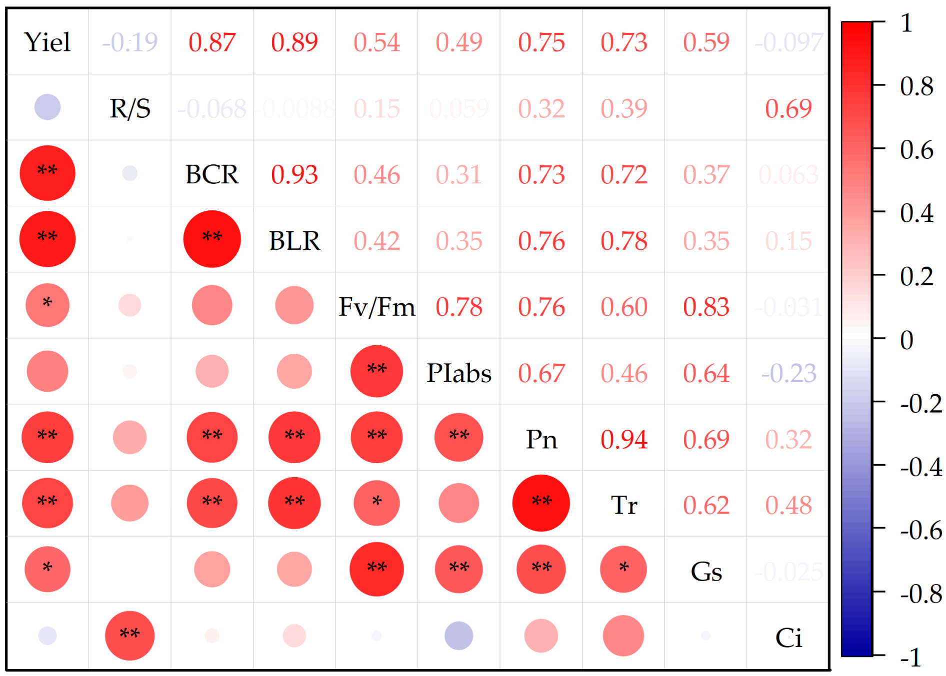

Figure 13. Correlation analysis of seed cotton yield, root production capacity, and photosynthesis parameters. Correlation coefficients vary from 1.0 (blue) to −1.0 (red). * and ** represent significant differences at $p < 0.05$ and $p < 0.01$ probability level. Pn, net photosynthetic rate; Tr, transpiration rate; Gs, stomatal conductance; Ci, intercellular CO_2 concentration. F_v/F_m, maximal quantum efficiency; PI_{abs}, photosynthetic performance index; R/S, root–shoot ratio; BCR, boll capacity of the root system; BLR, boll loading of the root system; Yield, seed cotton yield.

4. Discussion

The effects of film mulches [25–29] and planting density [5,7,24,26] on the cotton yield have been the subject of numerous studies. However, the suitable planting density in the arid cotton fields of southern Xinjiang when using plastic film mulching remains poorly understood. Our study's findings show that the moderate planting density (D2) increased root development capacity and photosynthetic capacity while also improving biomass and seed cotton yield with both plastic film mulching and no mulching across two years. Planting density and crop yield had a parabolic relationship when there was an adequate supply of nutrients, and densities that were too high and too low were not conducive to an improvement in the yield [19]. The appropriate planting density not only increased the cotton biomass and yield but also maximized the economic benefits. In our study, the highest economic income of cotton was found under D2, both with and without plastic film mulching. And the economic income of plastic film mulching was lower than that under no mulching in 2023. Moreover, reducing the planting density may also reduce some inputs of external means of production in the production process, such as pesticide inputs, without affecting yields. It was noteworthy that the seed cotton yield in 2022 was strikingly higher than in 2023, probably because cotton seedlings were damaged by low temperature and freezing in 2023.

Photosynthesis is the strongest factor impacting crop productivity, and it is also the basis for crop growth, development, and yield formation [30]. Planting density had a significant effect on crop photosynthetic production [18,31,32]. The SPAD value directly indicated the relative content of photosynthetic pigment [33,34]. The higher the content of photosynthetic pigments in cotton leaves, the greater the photosynthetic performance of the leaves and the greater the metabolic capacity of the plant [35]. In the present study, crops at low planting density (D1) and high planting density (D3 and D4) significantly decreased the SPAD value, with both plastic film mulching and no mulching, indicating that neither too high nor too low a density was conducive to increased leaf photosynthesis. In addition, Yan et al. [36] showed that higher planting density can decrease the photosynthetic capacity and photoassimilate accumulation. Our research also found that high planting density resulted in declines in Pn, Tr, and Gs and an increase in Ci. The limitation of these properties contributed to CO_2 uptake resistance and a stomatal limitation, thereby restraining the photosynthetic capacity via the lack of materials for photosynthetic assimilation and reduced water loss [37,38]. In addition, density was a critical factor coordinating to the contradiction of crop groups and individuals [39]. Crops at low planting density had better conditions for individual growth, but the population was insufficient and photosynthetic rate was low, resulting in a lower accumulation of photosynthetic material and yield [40,41]. High-density crops lead to oversized populations, and the leaves tend to shade each other [42], resulting in reduced Gs and leaf transpiration, thus inhibiting the photosynthetic capacity [18,43]. Further, moderate planting density (D2) had higher values on chlorophyll fluorescence parameters (F_v/F_m and PI_{abs}), with both plastic film mulching and no mulching, across two years, suggesting that optimum planting density helps to effectively utilize the limited light energy and improve the efficiency of light energy capture, thus improving the efficiency of energy conversion [44,45].

Another important factor in influencing the overall crop yield is the distribution of photosynthetic products in the root system and above the ground [46]. Planting density determines the population size and crop yield in agricultural fields and has an important impact on the morphological traits of the crop root system [47]. Increased planting densities can cause competition for limited nutrients and water between individual crop root systems [24,48], making root systems too large, which lowers the root–shoot ratio (R/S). The coordinated growth of plant roots and shoots was closely related to the crop yield [49,50], as a root system that is too large will consume excessive photosynthetic products, which will hinder the formation of reproductive organs [51], consequently reducing the yield. Meanwhile, key indicators of the relationship between the root system and reproductive organs were the boll capacity (BCR) and the boll loading (BLR) of the root system [11,15].

In this study, there were lower R/S and higher BCR and BLR under D2 relative to other treatments, with both plastic film mulching and no mulching across two years, and this result indicated that suitable planting density was conducive to reduced excess root growth, facilitating the distribution of photosynthetic products to the boll and the formation of cotton yields. Khan et al. [13] also reported that the increase in seed cotton yield at optimum density was primarily due to strong root growth and vitality, which enhanced the capacity of the roots to absorb nutrients and transfer them to the growing bolls. Further, from the first peak squaring stage until the boll opening stage, there was a highly significant positive link between the seed cotton yield, BLR, BCR, Pn, and Tr, according to correlation analysis. Therefore, these results indicate an improvement in leaf physiological traits and root production capacity, which raises the leaves' capacity for photosynthetic processes, thereby causing a rise in the seed cotton yield at a moderate planting density (D2).

Our data showed that the higher seed cotton yield under film mulching at optimal planting density (D2) was primarily attributed to improvements in the photosynthetic parameters and the enhancement of the balance between root and reproductive growth. This is related to optimizing the photosynthetic capacity of cotton, improving the distribution of photosynthetic products, and increasing the transport of photosynthetic products to the boll under appropriate planting densities. Therefore, we concluded that planting at an optimum density (18×10^4 plants ha^{-1}) under plastic film mulching would effectively strengthen the leaf photosynthetic capacity and root production capacity, thereby increasing the seed cotton yield in arid areas of southern Xinjiang.

5. Conclusions

Planting density and plastic film mulching significantly affected cotton root–shoot relationships, photosynthetic parameters, biomass, and seed cotton yield. Compared with no mulching, plastic film mulching increased chlorophyll fluorescence and photosynthetic parameters and had a greater effect on the cotton biomass, root development, and boll capacity of the root system, which, in turn, caused an increase in the seed cotton yield under various planting densities. However, the net income without plastic film mulching treatments was lower than that with plastic film mulching treatments at the same planting density. High planting density, both with and without plastic film mulching, reduced the SPAD value, reduced stomatal conductance (Gs) and leaf transpiration, weakened the light energy capture capacity, and had an clear negative impact on the photosynthetic capacity. Moderate planting density had a lower R/S and a higher BCR and BLR. In addition, by improving photosynthetic parameters and chlorophyll fluorescence parameters, the ability of assimilate transport to cotton bolls was increased under moderate planting density (D2), consequently increasing the biomass and seed cotton yield.

These results provide a reference for agricultural sustainability at a suitable planting density both with and without plastic film mulching in arid areas of the southern Xinjiang cotton fields.

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