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The Effect of Plant and Row Configuration on the Growth and Yield of Multiple Cropping of Soybeans in Southern Xinjiang, China

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Abstract: To study the optimal plant row configuration of the multiple cropping of soybeans that are suitable for planting in southern Xinjiang, a field experiment using soybean variety SN35 was carried out employing different plant row designs. Three row spacing treatments of 15 cm (H1), 30 cm (H2), and 45 cm (H3) and three density treatments of 52.56 million (M1), 55 million (M2), and 60 million (M3) plants per hectare were set up in this experiment to explore the effects of different plant row spacing configurations on agronomic traits, photosynthetic characteristics, dry matter accumulation, and the soybean yield of the multiple cropping of soybeans. The results showed that the soybeans' plant height, diameter, main stem node number, leaf shape index, leaf area index (LAI), leaf area duration (LAD), and pod dry matter distribution ratio increased gradually with the growth process. In contrast, the stem dry matter distribution ratio decreased gradually, and the leaf dry matter distribution ratio first increased and then decreased. The plant height of the soybeans treated with H2M3 was the highest, reaching 67.38 cm. The number of primary stem nodes of the soybeans treated with H1M3 was the highest, reaching 12.7 nodes. The stem diameter of the soybeans treated with H1M1 was the highest, reaching 0.64 cm. The leaf shape index of the soybeans treated with H3M1 was the highest, reaching 2.72. Intercellular CO_2 concentration closely affects the final yield; the correlation coefficients with the pod number per plant, seed number per plant, and yield reached 0.75, 0.78, and 0.87, respectively. The theoretical maximum hundred-grain weights under the H1M1 and H2M1 treatments were higher, reaching 20.33 g and 17.98 g, respectively. The H3M3 treatment had the most significant one-hundred-grain weight, reaching 21.27 g. The soybean yield of each density treatment was M3 > M1 > M2. With the increase in row spacing, the average pod number per plant, grain number per plant, grain weight per plant, and yield of soybeans decreased gradually, and the hundred-grain weight increased gradually. The yield of the density treatment with 60 million plants per hectare under 15 cm row spacing was the highest, reaching 6155.8 kg·hm^{-2}, followed by the density treatment with 60 million plants per hectare under 30 cm row spacing, reaching 5850.6 kg·hm^{-2}.

Keywords: soybean; high planting density; uniform plant distribution; yield; southern Xinjiang

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1. Introduction

The soybean is an annual herbaceous plant of Leguminosae. It is a crucial vegetable oil and protein raw material in people's lives. It is also a high-quality raw material for various industrial products such as food and feed [1–5]. However, China's soybean production is relatively low and relies heavily on imports to meet domestic consumer demand. In 2021, China's total soybean consumption will reach 111.7 million tons, while the total output will be less than 15% of the total consumption. In 2021, the total soybean imports will be 96.52 million tons [6,7]. At present, China has become the world's largest importer of soybeans. China's soybean crushing enterprises are dependent on the import of more than 89% of their soybean raw materials from external sources [6–8]. Therefore, increasing the soybean yield per unit area is significant in the effort to meet the needs of China's industrial production and the residents' living standards.

Planting density plays a vital role in the formation of soybean yield. Changing planting density can adjust the population structure of soybeans and can coordinate the ventilation and light transmittance; the soybean output can be increased by reasonably increasing the density [9–12]. The low density is conducive to the individual development of the plants, and the individual yield of the plants is improved. However, the population per unit area is small, and the potential of the population yield cannot be expressed. High-density planting leads to poor individual development, a large population per unit area, decreased population ventilation and light transmission capacity, and even lodging [13,14]. By constructing a reasonable plant spacing to ensure the number of populations per unit area, the quality of the individual development is guaranteed to produce a high yield. In the United States, a record soybean yield of 10,414 kg·ha^{-1} was recorded in 2007 in Missouri by Kip Cullers, with a planting density of 520,000 plants ha^{-1} [15]. In China, a record soybean yield of 6803 kg·ha^{-1} was obtained in Xinjiang Province in 2020, with a planting density of 300,000 plants·ha^{-1} [16]. Some scholars believe that higher seed yield is positively correlated with higher plant populations and that the soybean yield could increase significantly by 16.2%, 31.4%, 41.4%, and 46.7% for every increase in planting density of 45,000 plants ha^{-1}, within the range of 135,000 to 315,000 plants ha^{-1}; this shows that higher planting density improves seed yield [12,17]. However, high planting density or intensive planting alone does not necessarily lead to a higher grain yield of soybeans or other crops [18,19]. The uneven distribution of a single plant in a specific planting density affects plant growth and leads to yield loss of the crop canopy [20]. The uneven distribution of plants also leads to differences in the light environment within the plant population, affecting the development of soybean plants [21]. In addition, high-density planting reduces the leaf thickness and photosynthetic rate of soybeans, decreasing population light intensity and leading to a poor yield [22,23]. Therefore, studying how to ensure food security through reasonable planting density has become the primary problem we must solve.

Multiple cropping can improve the utilization efficiency of natural resources and reduce agricultural inputs. Meanwhile, Xinjiang has a vast area. In recent years, the climate has also developed into one which is warm and humid; the temperature has increased, the frost-free period has been extended, and the size of soybeans after wheat has gradually expanded. It is suitable for soybean growth and has a high environmental yield potential. However, the local soybean planting technology is relatively backward; the yield level is low, the quality is poor, and the production cost is high, which restricts the development of soybean production. The area is mainly flat farming; the primary soybean planting row spacing is 10–35 cm, and the density is 20–25 million plants per hectare. Due to the late start of the research on the multiple cropping of soybeans, the research on soybean planting is mainly focused on planting density, nitrogen, rhizobia, etc., and there is a lack of supporting high-yield cultivation techniques [24–26]. There are few reports on the progress of southern Xinjiang's soybean plant row configuration research. Therefore, based on the advantages of light and temperature resources in Xinjiang, this research aims to study the influence of plant row spacing changes on the growth and yield formation of multiple soybeans to strengthen the promotion of advanced planting technology and excellent varieties, provide some theoretical references for local agricultural production, and popularize different soybean producing areas according to local conditions to improve soybean yield in Xinjiang and even provide a guarantee of national food security.

2. Materials and Methods

2.1. Site Description

This experiment was carried out at the agronomy experimental station of Tarim University in Alar City, Xinjiang (40°32′20″ N, 81°17′57″ E), on the northern margin of the Tarim Basin from October 2021 to June 2021. The experimental field belongs to the warm temperate continental arid desert area, with an altitude of 1015 m and a frost-free period of 220 days; the previous crop was winter wheat. The soil organic matter content was 8.06 $g \cdot kg^{-1}$; the available phosphorus was 19.6 $mg \cdot kg^{-1}$; the available potassium was 117.6 $mg \cdot kg^{-1}$; the alkali hydrolyzed nitrogen was 34.7 $mg \cdot kg^{-1}$; and the pH was 7.8.

2.2. Experimental Design

The tested soybean variety is SN35, with branches, white flowers, long leaves, round seeds, light yellow umbilicus, yellow seed coat, and dull appearance; it is jointly cultivated by the Suihua Branch of Heilongjiang Academy of Agricultural Sciences and Xinjiang Fuquan Xinke Seed Industry Co., Ltd. It is a new variety with moderate to strong drought resistance, salt alkali resistance, and negative tolerance; its growth period is 118 days. The experiment adopted a two-factor split zone design. The row spacing treatments were at the following main plots (H): 15 cm (H1), 30 cm (H2), and 45 cm (H3); the planting density was the sub-region (M): 52.56 million (M1), 55 million (M2), and 60 million (M3) plants per hectare. Each community block had an area of 4.5 m × 2 m, for a total area of 9.0 m^2, with three replicates. In addition to the application of bottom fertilizer before planting, nitrogen, phosphorus, and potassium fertilizers were applied at the complete flowering stage, the entire pod stage, and the seed filling stage, respectively. The detailed fertilization content is shown in Table 1. At the complete flowering stage and entire pod stage of the soybeans, 98% potassium dihydrogen phosphate foliar fertilizer was applied twice at a rate of 4.5 kg/hm^2; all the fertilizers were obtained from the Yili Tianli Bio-Organic Fertilizer Manufacturing Co., Ltd. The other management measures were the same as those in the field. It was manually pulled on demand on 29 June 2021, and harvested on 7 October 2021.

Table 1. Data of four fertilization records.

Fertilizer Type	Bottom Fertilizer	Complete Flowering Stage	Entire Pod Stage	Seed Filling Stage
Nitrogen (kg/hm^2)	13.80	23.28	28.35	16.05
Phosphorus (kg/hm^2)	16.2	23.16	44.03	17.00
Potassium (kg/hm^2)	20.25	20.25	20.25	6.75

2.3. Determination and Methods

2.3.1. Agronomic Traits

At the four-node stage (V4) of soybean, ten representative soybean plants with uniform growth vigor were selected for listing treatment. The growth indexes, such as plant height, stem diameter, node number, leaf length, and leaf width were measured at the four-node stage (V4), complete flowering stage (R2), entire pod stage (R4), seed filling stage (R6), and complete maturity stage (R8). The natural height of the plant was measured using a tape measure, with the soybean cotyledon nodes as nodes. The diameter of the second internode of the main stem from the cotyledon node was measured using a vernier caliper. A ruler was used to measure the length of the central leaf vein and the widest part of the soybean's top three leaves, and the leaf shape index was calculated [1].

2.3.2. Leaf Area Index (LAI) and Leaf Area Duration (LAD)

Ten representative soybean plants with uniform and consistent growth were selected from the soybean treatment stages V4, R2, R4, and R6. The individual leaves were spread flat on a black screen for photography. After exporting the photos, the leaf area was calculated using IMAGE J 1.51j8 software, and LAI and LAD were calculated using Microsoft Office Excel 2021 software. The formula is as follows:

$$\text{LAI} = (\text{Plant leaf area}) \times (\text{Number of plants per unit land area})/(\text{Per unit field area});$$

$$\text{LAD } (\text{m}^2\cdot\text{d}) = [(L_1 + L_2)/2] \times (t_2 - t_1).$$

In the above formula, $t_2 - t_1$ is the number of days during the adjacent growth period, and L_1 and L_2 are the leaf areas of t1 and t_2, respectively.

2.3.3. Photosynthetic Characteristics

At the R2, R4, and R6 stages, mature soybean leaves with consistent growth were selected from each treatment. Six samples were randomly tested for each treatment, the net photosynthetic rate (Pn), stomatal conductance (Gs), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) of individual soybean plants were measured using the LI-6400XT portable photosynthetic measurement system [1,24].

2.3.4. Dry Matter Accumulation

Ten representative soybean plants with uniform and expected growth were selected. The stems and leaves of the plants at the V4 and R2 stages, the stems, leaves, and pods of the plants at the R4 and R6 stages, and the stems and pods of the plants at the R8 stages were put into envelope bags, respectively. The greens were killed in the oven at 105 °C for 0.5 h and dried to a constant weight at 80 °C. The dry weight of each organ was measured, and each organ's total dry matter accumulation at each growth stage was calculated [21,22].

2.3.5. Yield and Yield Components

In the R8 period, 1 m^2 in the middle of each plot was selected for the actual harvest and yield measurement. Ten representative soybean plants with consistent growth were selected for indoor testing. The number of pods per plant, the number of seeds per plant, the weight of the seeds per plant, and the 100-seed weight were measured (determined after drying to a 13.5% water content).

2.4. Data Analysis

Univariate analysis of variance was used to analyze the effects of planting density and plant distribution pattern on the measured parameters (including plant height, stem diameter, node number, leaf shape index, LAI, LAD, photosynthetic characteristics such as Pn, Gs, Tr, and Ci, dry matter accumulation, yield, and yield components). We conducted a regular distribution test and variance homogeneity test on the data of each indicator, and the results showed that the *p*-values were more significant than 0.05, indicating that the data were reliable. Using Data Processing System 9.5 software (Produced in Zhejiang, China), the classified data were tested using the least significant difference (LSD) method to detect differences between pairs of means. Correlation analysis was conducted between multiple trait indicators of the soybean and its yield; statistical comparisons were significant at $p < 0.05$. The leaf area was calculated using IMAGE J1.51j8 software, and LAI and LAD were calculated using Microsoft Office Excel 2021 software.

3. Results

3.1. Soybean Plant Traits

3.1.1. The Plant Height Characteristics

Plant height is one of the critical indicators of crop growth and development. There was no significant difference in the initial growth of the soybean in each treatment, but the plant height increased at the V4-R6 stage, and the growth rate tended to be stable after the R6 stage and reached the highest stop growth at the R8 stage. There was no significant difference in the early growth stage of the soybean in each treatment, and the difference began to appear at the R2 stage gradually (Figure 1). Under different row spacing treatment conditions, with the advancement of the growth process, the plant height of each treated soybean gradually increased with the increase in density, and the specific performance was M3 > M2 > M1. Under different density treatment conditions, the performance of the soybeans in each row spacing treatment was H2 > H1 > H3. The average plant height of the different row spacing treatments was H2 > H1 > H3. Among them, the average plant height of the H2 treatment was 62.45 cm, which was 4.69% and 12.76% higher than that of the H1 and H3 treatments, respectively. The average plant height of the different density treatments was M3 > M2 > M1.

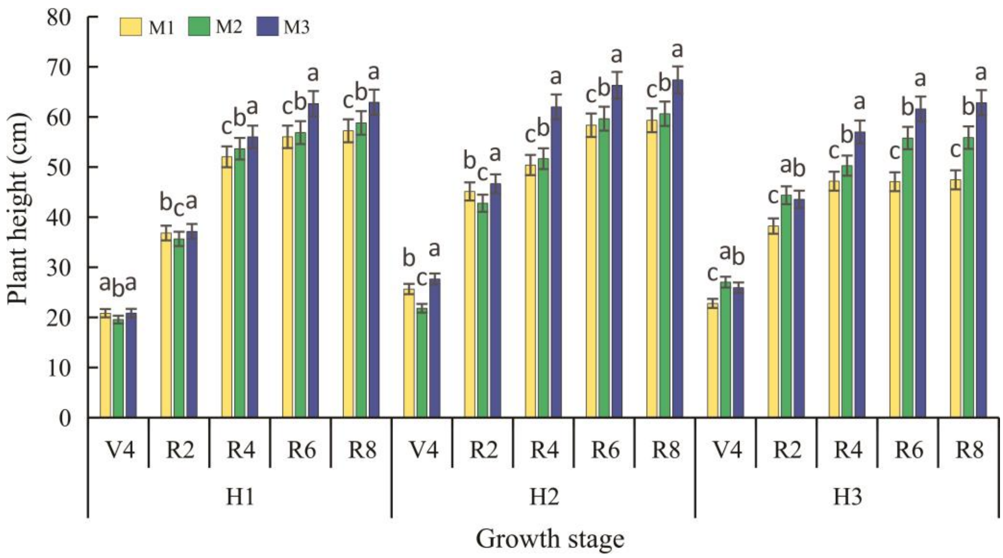

Figure 1. The plant height characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

3.1.2. The Stem Diameter Characteristics

Stem diameter is one of the main agronomic traits of soybeans, and it is also an important index to measure crop production performance. With the advance of the growth process, the stem diameter of the soybeans increased gradually; it tended to be stable at the R4 stage, stopped growing at the R6 stage, and decreased at the R8 stage, which may be due to the decrease in water in the mature stem of the soybean at the R8 stage, resulting in the decline in the stem diameter of the soybean. Under different density treatment conditions, the stem diameter of the soybean in each row spacing treatment was H1 > H2 > H3 at each growth stage. The stem diameter of the H1M1 treatment was the largest, and the stem diameter of the H3M3 treatment was the smallest, reaching 0.64 cm and 0.46 cm, respectively (Figure 2).

3.1.3. The Nodes Number of Main Stem Characteristics

In the whole growth period, different plant row configurations had other effects on the number of main stem nodes of the soybeans. With the advancement of the growth process, the number of central stem nodes of each treatment of the soybeans gradually increased. There was no significant difference in each treatment at the V4-R2 stage, and the difference began to appear progressively at the R2 stage, indicating that the effect of each treatment on the number of central stem nodes was not apparent at the V4-R2 stage and slowly began to play a role at the R2 stage (Figure 3). Under different row spacing treatment conditions, M3 treatment had the best effect on promoting the number of main stem nodes of the soybeans. Under the conditions of the H1 treatment, the number of soybean nodes treated with M1 and M2 was not significantly different, reaching 10.6 and 10.7, respectively. Under the different density treatment conditions, the number of main stem nodes of the H2 treatment under the M2 treatment was the highest, reaching 11.1, which was 3.74% higher than that of the H1 and H3 treatments.

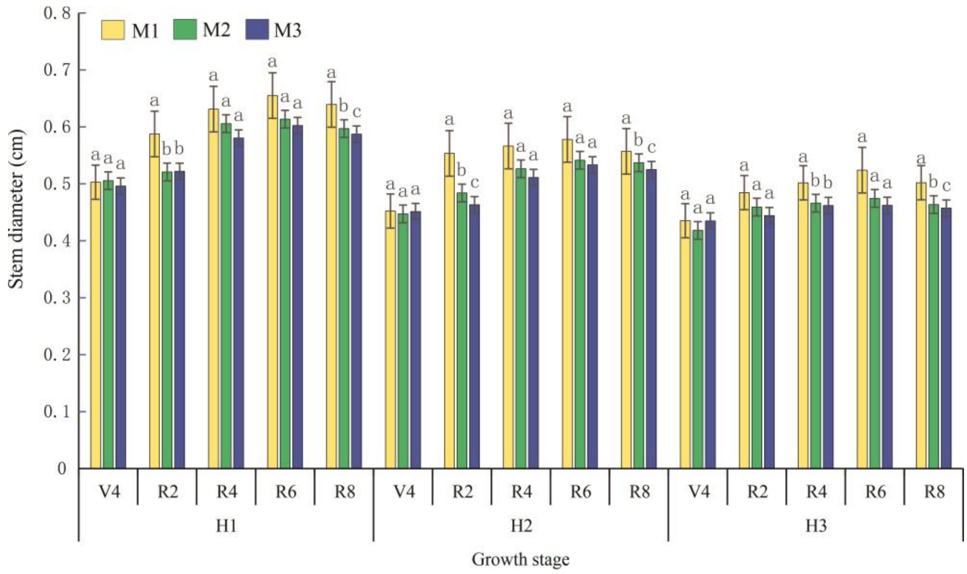

Figure 2. The stem diameter characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

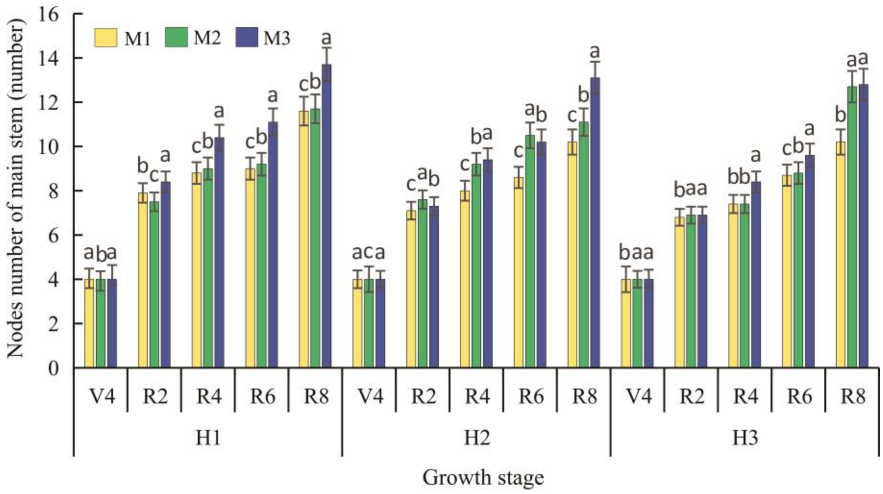

Figure 3. The nodes number of main stem characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

3.1.4. The Leaf Shape Index Characteristics

The soybean leaf shape index can reflect the plants' ventilation and light transmission ability. The leaf shape index of the soybeans increased gradually with the growth period. The leaf shape index of the V4-R2 stage rose the fastest; it gradually tended to be gentle at the R4 stage and reached the maximum at the R6 stage (Figure 4). The average leaf shape index of each row spacing treatment was H3 > H2 > H1, and the average leaf shape index of each density treatment was M1 > M2 > M3, indicating that increasing the row spacing and reducing the density were beneficial to the formation of the individual morphologies of the soybean plants. Among them, the H3M1 treatment had the highest leaf shape index of the soybeans, reaching 2.72, and the H1M3 had the lowest leaf shape index of 2.35.

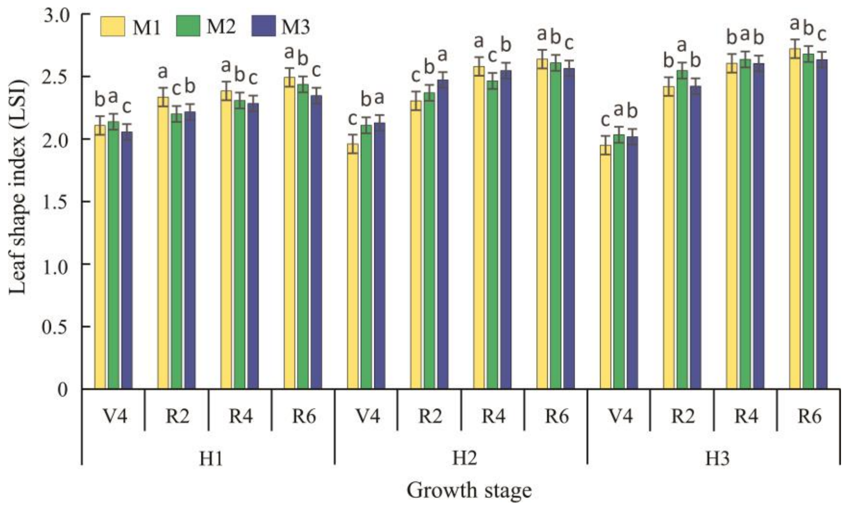

Figure 4. The leaf shape index characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

3.2. LAI and LAD Characteristics

Plant leaves are the most important organs for photosynthesis. The LAI is an essential factor affecting the photosynthetic capacity of soybean leaves, which can directly reflect the growth of plants. The soybean leaf area in each treatment showed an inverted 'V' curve. With the advancement of the growth process, the LAI gradually increased and reached the maximum at the R6 stage. At the R8 stage, the LAI value was zero due to the yellowing and shedding of the soybean leaves at the R8 stage (Figure 5). Under different row spacing treatment conditions, the LAI of each density treatment was M2 > M3 > M1. The H3M2 and H3M3 treatments were significantly higher than the M1 treatment, reaching 6.34 and 5.47, respectively, which were 56.08% and 34.76% higher than that of the M1 treatment. It can be predicted that the M1 treatment of soybean leaves is relatively fattening, which may not be conducive to the rapid accumulation of soybean yield in the later period. Under different density treatment conditions, the performance of each row spacing treatment was H2 > H3 > H1.

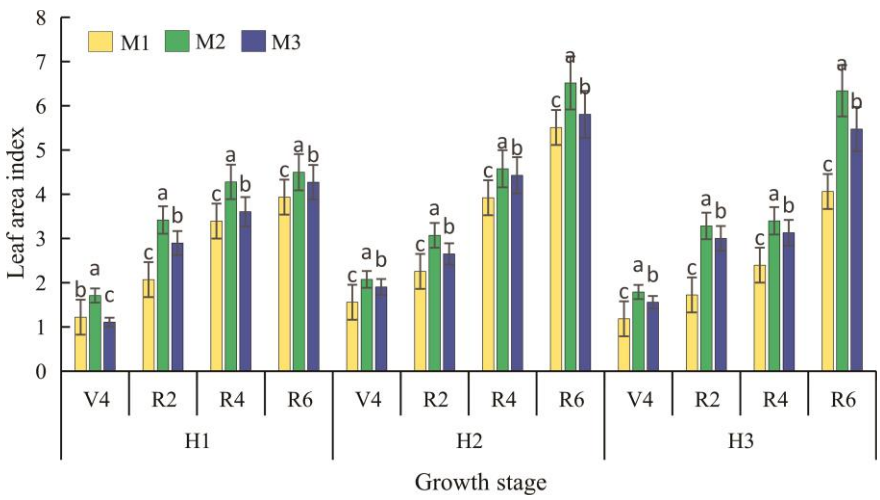

Figure 5. The LAI characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

LAD is one of the essential parameters indicating the photosynthetic performance of the crop population. The size of the crop leaf area and the time that the leaf remains green determine the strength of LAD, and the population of LAD affects the photosynthetic performance of the crop population. Under different row spacing treatment conditions, there was no significant difference in the performance of the three density treatments at the V4 and V4-R2 stages (Figure 6). The LAD of each density treatment increased significantly at the R2-R4 stage, and the growth rate slowed down after the R4 stage, reaching the maximum at the R4-R6 stage; the three density treatments were M2 > M3 > M1. Under the conditions of the H2 treatment, the LAD of the M2 treatment reached the maximum value of 83.19 $m^2 \cdot d$, which showed a significant difference compared to the M1 treatment and no significant difference compared to the M3 treatment. Under the conditions of the H1 and H3 treatments, the M2 treatment was significantly different from the M1 and M3 treatments. Under the different density treatment conditions, the three row spacing treatments were the same at the V4 and V4-R2 stages, and there were significant differences and rapid growth at the R2-R4 stages. The R4-R6 period reached the maximum value, and the LAD of the three row spacing treatments was the highest in M2.

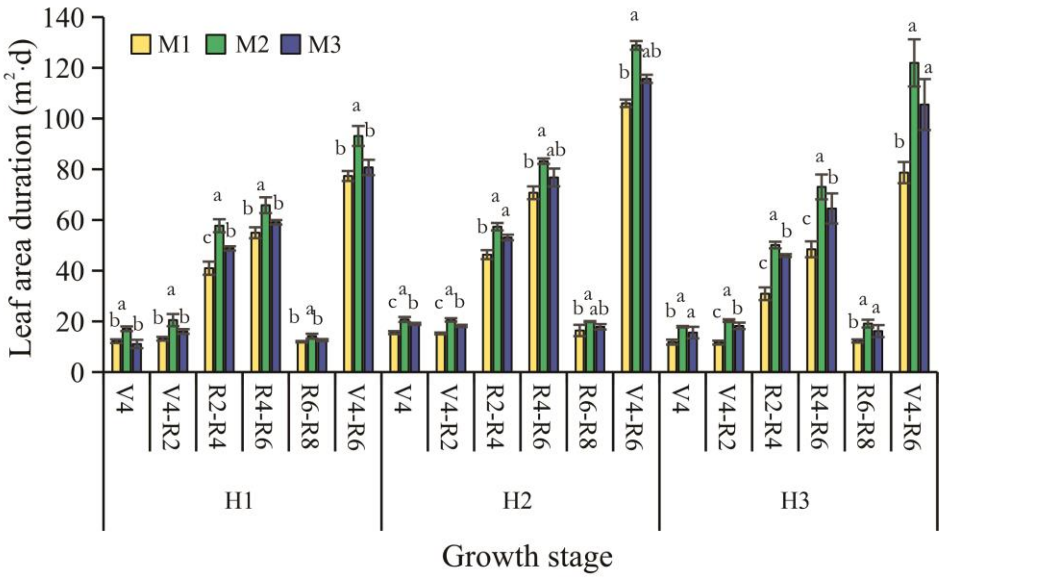

Figure 6. The LAD characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

3.3. *Photosynthetic Characteristics of Soybean*

Adequate light conditions and chlorophyll content can ensure that crops accumulate more substances for growth and development during photosynthesis. Reasonable planting density can improve crop light energy utilization and thus increase crop yield [21,23]. The net photosynthetic rate (Pn), stomatal conductance (Gs), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) of soybeans are effective parameters to reflect the photosynthesis of the plants.

3.3.1. The Net Photosynthetic Rate (Pn)

At the R2 stage, under the conditions of the H2 treatment, there was no significant difference in Pn among the three soybean density treatments. Under the treatment conditions of H1 and H3, the M2 treatment had the highest Pn for the three density treatments, and the M2 treatment was significantly different from the M1 and M3 treatments. The M2 treatment had the best promotion effect on the soybean Pn. Under the different density treatment conditions, the performance of each row spacing treatment was H2 > H3 > H1, among which the H2M2 treatment Pn was the largest, reaching 23.22 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Figure 7A).

At the R4 stage, Pn reached the maximum value. Under the different row spacing treatment conditions, the performance of each density treatment was M2 > M1 > M3, and the M2 treatment was significantly different from the M1 and M3 treatments (Figure 7B). At the R6 stage, the Pn of each treatment decreased, and the performance of each density treatment was M2 > M1 > M3, which was consistent with the performance of the R2 stage and R4 stage. Under the conditions of the M2 treatment, the Pn of the H1 treatment reached the highest level, at 18.39 $\mu mol \cdot m^{-2} \cdot s^{-1}$, followed by the H3 treatment at 16.96 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and the H2 treatment at 15.43 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Under the treatment conditions of M1 and M3, the performance of each row spacing treatment was H3 > H1 > H2 (Figure 7C).

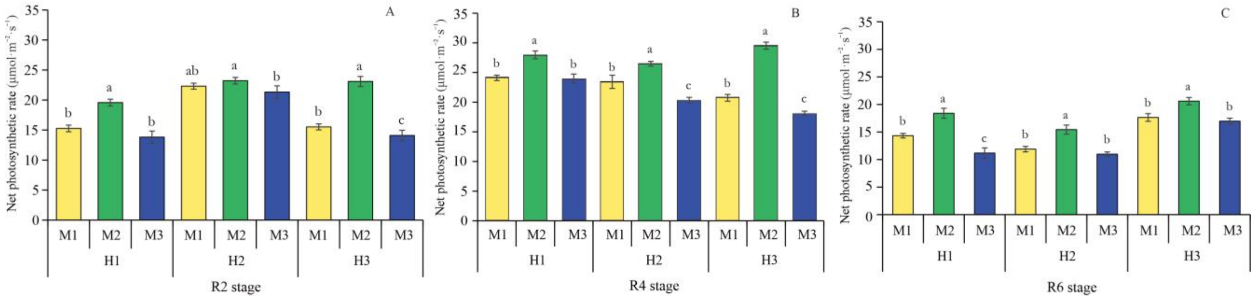

Figure 7. The Pn characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments. (**A**): At the R2 stage; (**B**): At the R4 stage; (**C**): At the R6 stage.

3.3.2. The Stomatal Conductance (Gs)

Under the different row spacing treatment conditions, each treatment in each growth period was M2 > M1 > M3. At the R2 stage, the Gs levels of the H1, H3, and M2 treatments were significantly higher than those of the M1 and M3 treatments. Under the conditions of the H2 treatment, the Gs levels of the M1 and M2 treatments were not much different; they were 0.38 $mol \cdot m^{-2} \cdot s^{-1}$ and 0.39 $mol \cdot m^{-2} \cdot s^{-1}$, respectively, but they were higher than that of the M3 treatment (Figure 8A). At the R4 stage, under the conditions of the H1 treatment, there was no significant difference between the three density treatments. Under the H2 and H3 treatment conditions, the M2 treatment was significantly different from the M1 and M3 treatments (Figure 8B). At the R6 stage, under the three row spacing treatment conditions, the M2 treatment and M1 and M3 treatments reached a significant level (Figure 8C). Under the different density treatments, at the R2 stage, the three row spacing treatments showed H2 > H1 > H3 (Figure 8A). At the R4 stage, under the conditions of the M1 and M3 treatments, the H1 treatment was the highest (Figure 8B). Under the conditions of the M1 and M2 treatments at the R6 stage, the Gs values of the row spacing treatment showed M1 > M3 > M2 (Figure 8C).

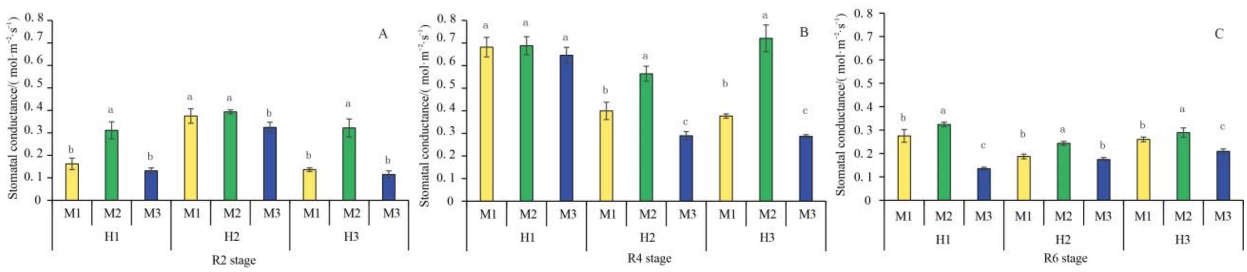

Figure 8. The Gs characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments. (**A**): At the R2 stage; (**B**): At the R4 stage; (**C**): At the R6 stage.

3.3.3. The Transpiration Rate (Tr)

Under the different row spacing treatment conditions, the density treatment at each growth stage was M2 > M1 > M3. At the R2 stage, under the conditions of the H1 and H2 treatments, the M2 treatment and M1 and M3 treatments reached a significant level, and the H2M2 treatment Tr was the largest, reaching 13.58 mmol·m^{-2}·s^{-1}. Under the conditions of the H3 treatment, the M2 treatment and M3 treatment reached significant differences, and the M2 treatment was the highest, reaching 9.08 mmol·m^{-2}·s^{-1} (Figure 9A). At the R4 stage, the M2 treatment reached a significant difference level compared to the M1 and M3 treatments (Figure 9B). In the R6 period, the Tr value was lower than that in the R4 period. Under the H1 treatment, the M2 treatment and M1 and M3 treatments reached a significant level. Under the H2 and H3 treatments, the M2 treatment was significantly different from the M3 treatment but not significantly different from the M1 treatment (Figure 9C). Under the different density treatment conditions, at the R2 stage, the three row spacing treatments showed H2 > H1 > H3 (Figure 9A). At the R4 stage, under the treatment conditions of M1 and M3, the Tr of the H1 treatment was the largest, H2 was the second, and H3 was the lowest, manifested as H1 > H2 > H3 (Figure 9B). At the R6 stage, under the M1 and M2 treatment conditions, the H1 treatment was the largest among the three row spacing treatments. Under the conditions of the M3 treatment, the three row spacing treatments showed H3 > H2 > H1 (Figure 9C).

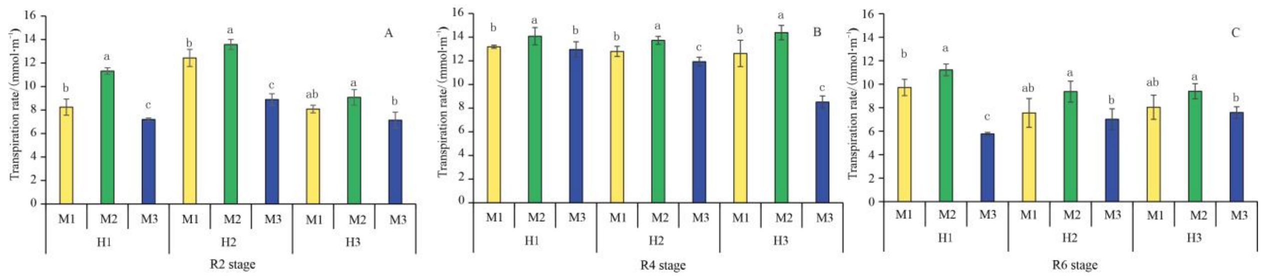

Figure 9. The Tr characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments. (**A**): At the R2 stage; (**B**): At the R4 stage; (**C**): At the R6 stage.

3.3.4. The Intercellular CO_2 Concentration of Soybean (Ci)

On the whole, with the advancement of the growth process, the Ci of the soybeans gradually increased to the maximum at the R4 stage and gradually decreased at the R6 stage (Figure 10). Under the different row spacing treatment conditions, at the R2 stage, under the H1 and H2 treatment conditions, the three density treatments showed M3 > M1 > M2, which was opposite to that of Pn, Gs, and Tr. Under the conditions of the H3 treatment, the Ci value of the M2 treatment was the largest, reaching 201.29 µmol·mol^{-1}, followed by M3, which was M2 > M3 > M1. At the R4 stage, the Ci of the soybeans reached the maximum value. Under the conditions of the H1 treatment, there was no significant difference between the M3 treatment and the M1 and M2 treatments. At the R6 stage, M3 was the largest, M1 was the second, and M2 was the lowest, which was opposite to that of Pn, Gs, and Tr. Under the different density treatment conditions, at the R2 stage, under the M1 and M3 treatment conditions, the three row spacing treatments showed H2 > H1 > H3 (Figure 10A). At the R4 stage, under the treatment conditions of M1 and M2, the performance of the three row spacing treatments was H1 > H3 > H2 (Figure 10B). In the R6 stage, under the treatment conditions of M1 and M3, the performance of the three row spacing treatments was H1 > H2 > H3 (Figure 10C).

3.4. Characteristics of Total Dry Matter Accumulation of Soybean

Under the different row spacing treatment conditions, each density treatment began to show significant differences at the R2 stage. Under the H1M2 and H2M1 treatment conditions at the R4 stage, the soybean dry matter was the highest, reaching 12.57 g and 13.65 g, respectively (Figure 11). At the R6 stage, the dry matter accumulation of each treatment increased significantly. The dry matter accumulation of the soybeans peaked at the R8 stage, and each treatment reached a significant difference level; each treatment was M1 > M3 > M2. Among them, the dry matter accumulation of the H3M1 treatment reached the highest level at 29.34 g, the H1M2 treatment reached the lowest level at 21.95 g, and the H3M1 treatment was 7.39 g more than the H1M2 treatment. Under the different density treatment conditions, there was no significant difference at the V4 stage. In the R2 period, the treatments gradually showed differences. At the R4 stage, under the conditions of the M1 treatment, the size of each row spacing treatment led to H2 > H1 > H3. At the R6 stage, the dry matter accumulation of the soybeans increased rapidly. Under each density treatment, the H2 and H3 treatments were significantly higher than the H1 treatment, and the H2 and H3 treatments and the H1 treatment reached a significant difference level. At the R8 stage, the dry matter accumulation of each treatment reached the peak, and the specific performance was H3 > H2 > H1.

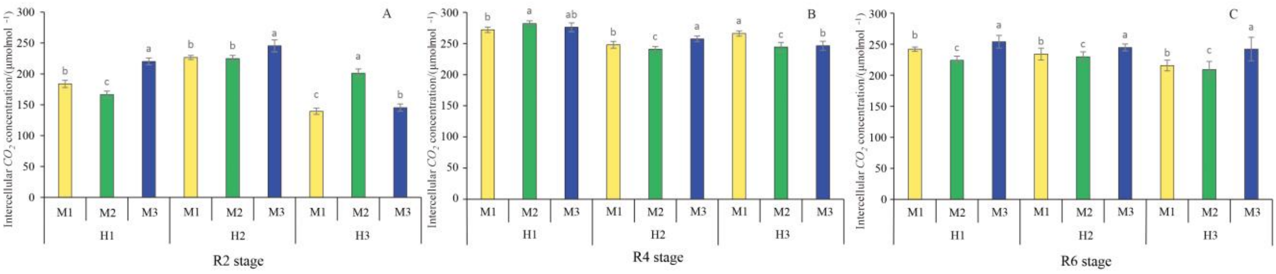

Figure 10. The Ci characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments. (**A**): At the R2 stage; (**B**): At the R4 stage; (**C**): At the R6 stage.

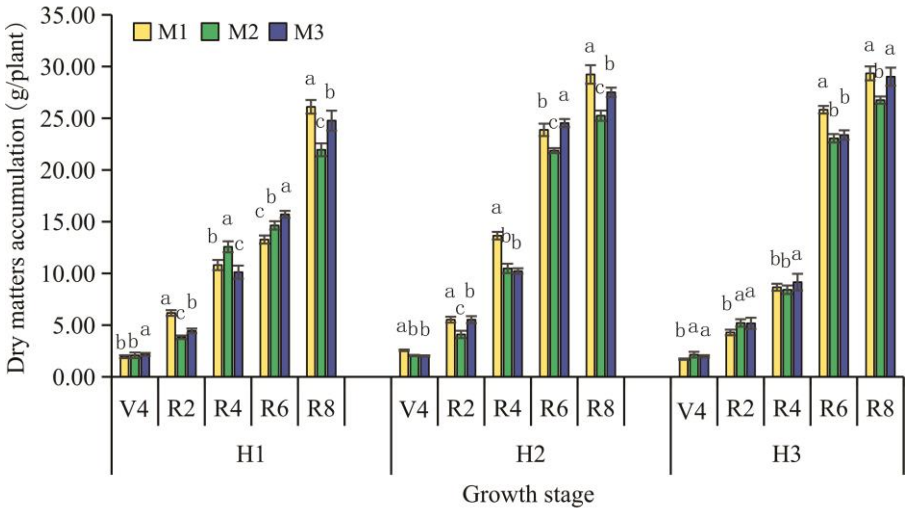

Figure 11. The dry matter accumulation characteristics of soybean replanted under different plant row spacing configurations. Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments.

3.5. Characteristics of Yield and Yield Components of Soybean

The different row spacing and densities mainly increased the soybean yield by affecting the number of pods per plant, the number of grains, the 100-grain weight, and other indicators. Under the different row spacing treatment conditions, the yield and the constituent factors of the M2 treatment of each density treatment were significantly different from those of the M1 and M3 treatments, and the three row spacing treatments were the lowest. Under the conditions of the H1 treatment, the pod number per plant, grain number per plant, 100-grain weight, and yield of the M3 treatment were the highest, followed by M1 treatment. Under the H2 and H3 treatments, the yield and components of the three density treatments were the highest in the M3 treatment, followed by the M1 treatment, and the specific performance was M3 > M1 > M2. The number of pods and seeds per plant under the H2M3 treatment reached 40 and 85, respectively. The number of pods per plant under the H2M2 treatment was the lowest, reaching 26.4, which was 13.6 less than that under the H2M3 treatment. The number of grains per plant in the H3M2 treatment was the lowest, reaching 55.7 grains, which was 29.3 grains less than in the H2M3 treatment. The grain weight per plant of the H1M1 treatment was the largest, reaching 15.4 g, and the grain weight per plant of the H3M2 treatment was the lowest, 10.8 g. The 100-grain weight of the H3M3 treatment was the largest, and the 100-grain weight of the H1M2 treatment was the lowest, at 19.9 g and 18.1 g, respectively (Table 2).

Table 2. Yield and its components of soybean under different treatments.

Row Space	Density	Pod Number per Plant	Seed Number per Plant	Seed Weight per Plant (g)	100-Seed Weight (g)	Yield (kg·hm^{-2})
H1	M1	34.7 ± 0.2 bB	80.0 ± 0.6 aA	15.4 ± 0.8 aA	18.6 ± 0.3 bB	5650.0 ± 104.9 aAB
	M2	33.1 ± 0.4 cC	67.0 ± 1.0 bB	13.2 ± 0.4 bA	18.1 ± 0.3 cB	5074.3 ± 83.0 bB
	M3	36.3 ± 0.5 aA	81.2 ± 1.5 aA	14.7 ± 0.5 aA	19.7 ± 0.1 aA	6155.8 ± 70.0 aA
H2	M1	36.8 ± 0.3 bB	81.4 ± 1.3 bB	14.8 ± 0.3 aA	19.2 ± 0.1 bAB	5440.1 ± 74.6 bA
	M2	26.4 ± 0.3 cC	59.3 ± 1.0 cC	11.3 ± 0.5 bB	18.7 ± 0.2 cB	4350.5 ± 38.1 cB
	M3	40.0 ± 0.6 aA	85.0 ± 1.0 aA	13.9 ± 0.7 aA	19.7 ± 0.2 aA	5850.6 ± 26.7 aA
H3	M1	29.3 ± 0.5 aA	68.6 ± 1.0 aA	13.3 ± 0.1 aA	19.7 ± 0.1 aAB	4886.0 ± 35.8 bB
	M2	20.3 ± 0.4 bB	55.7 ± 0.8 bB	10.8 ± 0.4 bB	19.4 ± 0.1 bB	4142.6 ± 41.7 cC
	M3	30.0 ± 0.7 aA	70.0 ± 0.8 aA	12.6 ± 0.6 aA	19.9 ± 0.1 aA	5283.6 ± 47.5 aA
Mean of row space	H1	34.7 ± 0.4 aA	76.0 ± 1.0 aA	14.4 ± 0.7 aA	18.8 ± 0.2 cB	5626.7 ± 51.8 aA
	H2	34.4 ± 0.5 aA	75.3 ± 1.0 aA	13.4 ± 0.6 abAB	19.2 ± 0.2 bAB	5217.7 ± 65.7 bB
	H3	26.6 ± 0.7 bB	74.7 ± 0.8 bB	12.2 ± 0.4 bB	19.7 ± 0.1 aA	4756.1 ± 62.2 cC
Mean of density	M1	33.6 ± 0.4 bB	76.7 ± 0.9 bB	14.5 ± 0.5 aA	19.2 ± 0.2 bB	5323.7 ± 34.6 bB
	M2	26.6 ± 0.5 cC	60.6 ± 0.8 cC	11.8 ± 0.5 bB	18.7 ± 0.2 cB	4522.5 ± 31.9 cC
	M3	35.4 ± 0.7 aA	78.7 ± 1.0 aA	13.7 ± 0.7 aA	19.7 ± 0.1 aA	5763.3 ± 35.9 aA
F	H	7.36 *	9.72 *	28.11 **	5.12	40.78 **
	M	7.68 *	23.90 **	45.94 **	7.54 *	82.25 **
	H×M	300.29 **	248.73 **	5.42 **	23.92 **	1.55 *

Note: Different lowercase and uppercase letters in the same column indicate significant differences at 5% and 1% levels for different treatments. * and ** denote significant differences at 0.05 and 0.01 probability levels.

4. Discussion

4.1. Effects of Plant Row Configuration on Soybean Plant Traits

Planting density determines the size of the crop population, and different row spacing determines the uniformity of the crop population. Only reasonable row spacing and planting density can produce higher yields while fully using external resources [27]. The results of this experiment showed that the plant height of the soybeans increased gradually with the increase in density. The plant height of the soybeans treated with H2M3 was the highest. This may be because even though the high density of the H2M3 treatment leads to the increase in the leaf coverage of soybean plants, the appropriate row spacing treatment can make the soybean row spacing ventilation better, which is more conducive to the growth of soybean plant height.

Stem diameter is an important index with which to judge the strength of plant growth, which is related to the lodging resistance of soybeans and reflects the robustness of seedlings to a certain extent. Reducing the planting density can significantly increase the stem diameter, but when the planting density is too high, the change in stem diameter is not obvious. This may be due to the high planting density, the fierce competition for nutrients and space between plants, and the death of some plants because of weak competitiveness; so, the change in soybean stem diameter is small [28,29]. The H1M1 treatment had the largest stem diameter, indicating that the H1M1 treatment had the best effect on the growth of soybean stem diameter and was the most conducive to the growth of soybean stem diameter and the better shaping of the soybean plant type.

The pods mostly grow at the stem nodes on the main stem. The number of nodes on the main stem is related to the yield of soybeans. Therefore, the number of nodes on the main stem is one of the important indexes in the process of soybean seed testing. Some scholars have shown that the number of main stem nodes decreases with the increase in density due to the serious deterioration of individual nutrition, light, and growth space after the exceeding of a certain density [29]. In this experiment, under the conditions of the M2 treatment, the number of main stem nodes of the H2 treatment was the highest, reaching 11.1, which was 3.74% higher than that of the H1 and H3 treatments. The average number of main stem nodes of each row spacing treatment was H1 > H2 > H3, showing a decreasing trend with the increase in row spacing. The average number of nodes in the main stem of each density treatment was M3 > M2 > M1, indicating that the number of nodes in the main stem of the soybeans increased with the increase in density. In summary, appropriate crop population distribution can optimize the canopy structure of the crop population and regulate the contradiction between individual plants and the population.

Leaf morphology is an important part of plant morphogenesis. The leaf shape index is an important parameter of plant leaf shape change, which can reflect the ventilation and light transmittance of the crop canopy [30,31]. Within a certain density range, the leaf shape index of the tested varieties increased with the increase in density, especially those the varieties with a high-density tolerance. However, when the density exceeded a certain range (greater than 37.5 million plants per hectare), the leaf shape index decreased, which was considered to be the reason why the upper leaves of the plant could grow freely under low-density conditions, which were more conducive to canopy ventilation and light transmission [32,33]. In this experiment, the leaf shape index of the M1 treatment was the highest, followed by M2, and M3 was the lowest. The density had a significant effect on the functional traits of the soybean leaves. The leaf shape index of each row spacing treatment was H3 > H2 > H1, indicating that the leaf shape index gradually increased with the increase in row spacing; this indicated that increasing row spacing and reducing density were conducive to the increase in the leaf shape index, which was conducive to the formation of soybean plant morphology.

4.2. Effects of Plant Row Configuration on LAI and LAD

The leaf area index determines the productivity of crops and affects the interaction between the surface and the atmosphere, and it is closely related to canopy photosynthesis, transpiration, and productivity [25,29]. Studies have shown that the LAI increases with the increase in density [9,14]. This study showed that with the advancement of the growth process, the LAI gradually increased and reached the maximum at the R6 stage. At the R8 stage, the soybean leaves turned yellow, and they fell off at the R8 stage, resulting in an LAI of 0. Row spacing affects plant growth and development by affecting the utilization of the crops' light, water, and nutrient resources. Appropriate row spacing can make the plant distribution more uniform, and increasing the LAI can reduce the light leakage loss [34].

The photosynthetic potential is determined by the size of the leaf area and the length of the leaf function period, which represent the crops' production potential. It is an important physiological index of crop production capacity and reflects the photosynthetic performance of the soybean population [35–39]. From the analysis of the whole growth stage, under different row spacing treatment conditions, the LAD of the soybeans in each density treatment showed M2 > M3 > M1; under different density treatments, the LAD of the soybeans under each row spacing treatment was H2 > H3 > H1. Among them, the LAD of the soybeans treated with H2M2 was the highest, reaching 128.86 $m^2 \cdot d$. The LAI was the highest, indicating that the spatial distribution of the individual leaves of the soybean plants treated with H2M2 was the best. Photosynthesis was the strongest; this could effectively improve the photosynthetic performance of the soybean population and make full use of the photosynthetic advantages. The LAD of the soybeans treated with H1M1 was the lowest, reaching 77.34 $m^2 \cdot d$. The possible reasons were that the row spacing was reduced, the ventilation and the light transmission ability between the soybean rows were weakened, the leaves grew faster within a certain period, and the transfer of excessive nutrients to vegetative organs was less, which in turn affected the improvement of grain yield.

4.3. Effects of Plant Row Configuration on Photosynthetic Characteristics

The net photosynthetic rate (Pn), stomatal conductance (Gs), transpiration rate (Tr), and intercellular CO2 concentration (Ci) of soybeans are effective parameters that reflect the photosynthetic capacity of plants [40–42]. As the growth process progressed, the Pn, Gs, Tr, and Ci of the soybeans in this experiment showed a single peak curve trend, according to which they first increased and then decreased, reaching their maximum value at the R4 stage. The different row spacing and density treatments had other effects on the effective photosynthetic parameters of the soybeans. Among them, the H3M2 treatment had the highest Pn, Gs, and Tr among all the treatments, indicating that its soybeans had the most robust photosynthetic performance, which can promote material circulation and transportation in the plant body, improve leaf photosynthetic efficiency, promote the accumulation of photosynthetic products, and lay a good foundation for soybean high yield.

4.4. Effects of Plant Row Configuration on Dry Matter Accumulation

The accumulation of total dry matter is the foundation of crop yield formation and is also one of the important agronomic traits for unleashing the soybean's advantageous potential [43,44]. The accumulation of dry matter during soybean growth is the main factor contributing to the formation of the soybean plant's final yield. There is a significant positive correlation between dry matter accumulation and yield, and increasing planting density within an appropriate range is beneficial for the accumulation and distribution of dry matter in the population and an increase in grain yield [45,46]. The dry matter accumulation of different density treatments at the R8 stage of this experiment showed M1 > M3 > M2. The spatial structure of the M1-treated soybeans was more suitable for soybean growth than the M2 and M3 treatments, and the development of the soybean plants was the best. In addition, the increase in row spacing significantly increased the dry matter accumulation after flowering. During the soybeans' growth and development process, nutritional growth stopped by the R6 stage when the plant's appearance was finalized. Most of the plant's nutrients are supplied for grain growth. The H1M1 and H1M3 treatments accumulated the maximum dry matter during the R6-R8 stage, reaching 12.83 g and 9.06 g, respectively, indicating that the H1M1 and H1M3 treatments had the greatest impact on soybean yield. According to the difference significance test, the interaction effect of row spacing and density on the dry matter accumulation of the soybeans at each growth stage is highly significant at the level of difference. The impact of planting density on soybean yield is mainly reflected in the accumulation and distribution of dry matter in the middle and later stages of growth and development [47,48]. As the density increases, the dry mass of the stem shows a trend of first increasing and then decreasing, while that of the pods is the opposite. The possible reason is that high density leads to less photosynthetic accumulation in soybeans, resulting in intense competition for nutrient absorption within a limited land area and lower dry matter accumulation in various plant organs. At the R8 stage, all the density treatments showed that the M2 treatment had the highest proportion of dry matter distribution in the soybean stems. In contrast, the M3 treatment had the highest proportion of dry matter distribution in the pods and fruits, reaching over 88%. This indicates that M2 treatment has the best effect on the growth of soybean plant morphology and that M3 treatment promotes soybean yield.

4.5. Effects of Plant Row Configuration on Yield and Yield Components

The size of the crop population is determined by planting density. In contrast, the uniformity of crop population distribution is determined by row spacing configuration [49]. The yield of crops depends on factors such as planting density, effective pods per plant, pod seeds, and 100-seed weight. Increasing the planting density is beneficial for improving soybean yield [50]. This experimental study shows that the number of pods per plant, the number of seeds per plant, the weight of 100 seeds, and the yield of the M3 treatment are the highest, and the yield of soybeans under each density treatment is M3 > M1 > M2. As the row spacing increases, the average number of pods per plant, the number of seeds per plant, the weight of the seeds per plant, and the yield of soybeans gradually decrease, while the weight of 100 seeds gradually increases. Among them, the H1M3 treatment has the highest yield, reaching 6155.8 kg·hm^{-2}, followed by H2M3, reaching 5850.6 kg·hm^{-2}, indicating that the H1M3 and H2M3 treatments can significantly increase soybean yield. Previous studies have shown that increasing the number of pods per plant can increase soybean yield. The number of grains per plant and the weight of the grains per plant significantly impact yield, while the impact of the 100-grain weight on yield is minimal compared to the other traits [51–53]. In this study, based on the significance test (*F*-value) of differences, it can be seen that row spacing treatment showed significant differences in the number of pods and grains per plant and extremely significant differences in grain weight and yield per plant. Density treatment showed significant differences in the number of pods per plant and the weight of 100 grains, while it showed extremely significant differences in the number of grains per plant, the weight of the grains per plant, and the yield. The row spacing and density interaction show extremely significant differences in various soybean yield components (Table 2).

4.6. Correlation Analysis between Soybean Plant Traits, Photosynthetic Parameters, and Yield Components

There is a significant correlation between plant height and the number of main stem nodes, indicating that plant height is most affected by the number of main stem nodes. There is a significant positive correlation between stem diameter and grain weight per plant, while there is a significant negative correlation with leaf shape index and 100-grain weight. This indicates that larger stem diameter is beneficial for increasing grain weight per plant, thereby increasing yield (Figure 12A). Correlation analysis of the photosynthetic parameters revealed a significant positive correlation between Gs and Tr, indicating a significant relationship between the level of leaf photosynthetic capacity and plant leaf transpiration, as well as the degree of stomatal opening and closing. The Ci in the leaves has the most significant positive correlation with pod number per plant, seed number per plant, and yield; the correlation coefficients reached 0.75, 0.78, and 0.87, respectively, indicating that Ci not only affects the photosynthetic rate of the leaves, but also closely affects the final yield (Figure 12B). The correlation analysis of the constituent factors and yield under different row spacing and density treatments shows a highly significant positive correlation between soybean yield, pods per plant, grains per plant, and grain weight per plant. Yield is positively correlated with 100-grain weight, indicating that the determining factors affecting yield are pods per plant, grains per plant, grain weight per plant, and 100-grain weight per plant. The correlation coefficient between the number of grains per plant and soybean yield is the highest, reaching 0.94, while the correlation coefficient between the weight of 100 grains and yield is the lowest, reaching 0.24. The weight of 100 grains is positively correlated with the number of pods per plant and the number of grains per plant while negatively correlated with the weight of grains per plant. An increase in 100-grain weight reduces the grain weight per plant of soybeans; so, the smaller the 100-grain weight, the greater the grain weight per plant and the higher the yield.

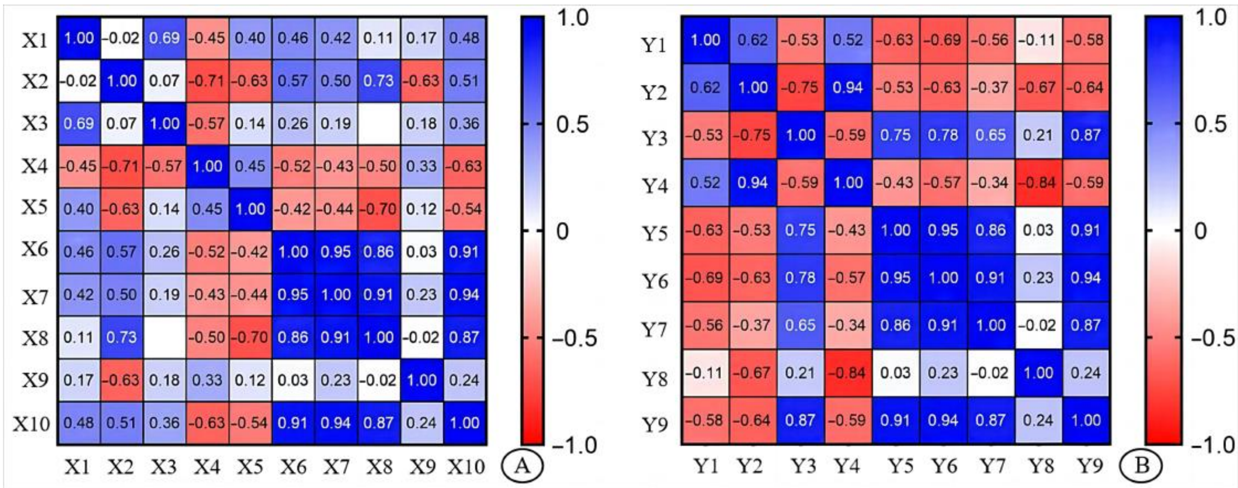

Figure 12. Heat map for correlation analysis between soybean plant traits, photosynthetic parameters, and yield components. (**A**) Correlation analysis between soybean plant traits and yield components (X1: plant height, X2: stem diameter, X3: node number of main stem, X4: leaf shape index, X5: LAI and LAD, X6: pod number per plant, X7: seed number per plant, X8: seed weight per plant, X9: 100-seed weight, X10: yield); (**B**) correlation analysis between soybean photosynthetic parameters and yield components (Y1: Pn, Y2: Gs, Y3: Ci, Y4: Tr, Y5: pod number per plant, Y6: seed number per plant, Y7: seed weight per plant, Y8: 100-seed weight, Y9: yield).

5. Conclusions

The yield of the density treatment with 60 million plants per hectare under 15 cm row spacing was the highest, reaching 6155.8 kg·hm^{-2}, followed by the density treatment with 60 million plants per hectare under 30 cm row spacing, reaching 5850.6 kg·hm^{-2}. The density of 52.56 million (M1) plants per hectare was beneficial to the increase in dry matter accumulation in soybean planting in southern Xinjiang. Sixty million (M3) plants per hectare had the best effect on soybean yield components and yield improvement. In summary, this research could provide some theoretical references for local agricultural production; it is recommended that reasonable cultivation measures are taken in actual production. In the R6-R8 period, the pod dry matter was the highest in the vegetative organs, and the pod dry matter accounted for more than 85% in the R8 period; irrigation and fertilization management should be appropriately strengthened.

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