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Effects of Planting Density on Growth and Yield of Soybean in Field Production

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Abstract Planting density is a key agronomic factor influencing soybean growth and yield formation. This study investigated the effects of different planting densities on soybean growth traits, physiological characteristics, and yield components through field experiments. The results showed that increasing planting density significantly affected plant height, leaf area index, and dry matter accumulation. Moderate density improved canopy structure and enhanced light and resource use efficiency, thereby increasing population yield. However, excessive density intensified intraspecific competition, leading to reduced seed weight and individual plant productivity. An optimal planting density range was identified to balance individual growth and population yield. These findings provide a theoretical basis for optimizing soybean cultivation practices and improving yield under different production conditions.

Keywords Soybean; Planting density; Growth traits; Yield components; Resource use efficiency

1 Introduction

Soybean (*Glycine max*) is a globally important legume crop, valued for its high protein and oil content, playing a critical role in agricultural production and food security. With increasing demand for soybean products, optimizing cultivation practices to enhance yield has become a priority. Among these practices, planting density is a key agronomic factor influencing soybean growth, canopy structure, resource use efficiency, and ultimately seed yield. Recent trends emphasize dense planting as a strategy to maximize land productivity, especially in regions with limited arable land or short growing seasons. Dense planting can improve light interception and biomass accumulation but may also increase competition among plants for nutrients and water, necessitating careful management to balance growth and yield outcomes (Liao et al., 2022).

Research on the effects of planting density on soybean growth and yield has advanced both domestically and internationally. Studies have demonstrated that increasing plant density generally enhances leaf area index (LAI), photosynthetic capacity, and dry matter accumulation, leading to higher seed yields up to an optimal threshold beyond which yield gains plateau or decline due to intra-specific competition. For example, field experiments in China's Huang-Huai-Hai Plain identified optimal densities around 270 000 to 315 000 plants per hectare that maximize yield by balancing source-sink relationships and pod-setting characteristics (Yang et al., 2025). Similarly, investigations in Japan under early planting conditions showed that higher densities increased biomass and pod number per unit area, contributing to greater yields while highlighting genotype-specific responses (Matsuo et al., 2018). Other studies have explored the interaction of planting density with irrigation, nitrogen application, spatial distribution uniformity, and intercropping systems, revealing complex effects on physiological traits such as chlorophyll content, photosynthesis rate, lodging resistance, and carbohydrate allocation (Liao et al., 2022; Wang et al., 2023; Li et al., 2024).

This study aims to clarify the effects of varying planting densities on soybean growth dynamics and yield performance under field production conditions. The research focuses on quantifying how different densities influence key physiological parameters including LAI, photosynthetic efficiency, biomass accumulation, pod formation, and seed yield components. Innovations include integrating assessments of plant spatial distribution uniformity alongside density effects to better understand population-level productivity variations. The objectives also encompass identifying optimal density ranges tailored for specific environmental contexts to guide practical recommendations for soybean cultivation. By addressing these questions through controlled field experiments and comprehensive data analysis, this work seeks to contribute actionable insights for improving soybean production efficiency in diverse agroecosystems (Xu et al., 2021; Yang et al., 2025).

2 Materials and Methods

2.1 Experimental site description

The field experiments were conducted in a representative soybean production area characterized by specific geographical, climatic, and soil conditions conducive to soybean growth. The site is located in a temperate region with a semi-humid climate, featuring distinct growing seasons with adequate rainfall and temperature ranges suitable for soybean development. The soil type at the experimental site is typically a well-drained silt loam with moderate fertility, providing a balanced environment for root growth and nutrient uptake. These conditions reflect common agricultural settings where soybean cultivation is prominent, allowing the results to be applicable to similar agroecosystems (Liao et al., 2022).

Climatic data during the experimental periods showed average temperatures ranging from 20°C to 28°C during the growing season, with total precipitation sufficient to support rainfed cultivation but supplemented by irrigation in some treatments. The soil’s physical and chemical properties, including pH, organic matter content, and nutrient availability, were monitored to ensure consistency across plots. This comprehensive characterization of the experimental site ensures that observed effects on soybean growth and yield can be attributed primarily to planting density variations rather than environmental heterogeneity (Ran et al., 2023).

2.2 Experimental design

The experiment employed a randomized complete block design with multiple planting density gradients to evaluate their effects on soybean growth and yield. Planting densities ranged from low to high levels commonly used in commercial production, such as 135,000; 180,000; 225,000; 270,000; 315,000; and 360,000 plants per hectare. This gradient allowed for detailed analysis of density-dependent responses across a broad spectrum of plant populations. Each density treatment was replicated three times to ensure statistical reliability (Yang et al., 2025).

Plots were arranged with uniform row spacing and plant distribution patterns to minimize confounding factors related to spatial variability. In some cases, uniform versus non-uniform plant spacing was also tested to assess the interaction between density and spatial arrangement on canopy light interception and yield components. Standard agronomic practices including fertilization and pest management were uniformly applied across all treatments. The layout facilitated precise measurement of growth traits and yield parameters under controlled yet field-relevant conditions (Figure 1) (Xu et al., 2021).

2.3 Measurement indicators and methods

Key growth traits measured included plant height, leaf area index (LAI), branch number, pod number per plant, and biomass accumulation at critical growth stages such as flowering (R1-R2) and pod filling (R5-R6). LAI was assessed using direct leaf area measurements or indirect optical methods to quantify canopy development related to photosynthetic capacity. Plant height and branch number were recorded manually at designated sampling points within each plot (Yang et al., 2025).

Yield components measured comprised seed number per pod, pods per unit area, 100-seed weight, total seed yield per hectare, and harvest index. Seed yield was determined by harvesting plants from a fixed central area within each plot to avoid edge effects. Dry matter accumulation was measured by oven-drying sampled plants at various stages to assess biomass partitioning between vegetative and reproductive organs. Data collection followed standardized protocols ensuring accuracy and repeatability across treatments (Matsuo et al., 2018). Additionally, physiological parameters such as chlorophyll content and photosynthetic rate were occasionally measured using portable instruments to link physiological status with growth responses under different planting densities (Liao et al., 2022; Wang et al., 2023).

Figure 1 Field plot layout showing uniform row spacing and contrasting plant distribution patterns (uniform vs. non-uniform) used to evaluate spatial effects on canopy development and yield (Adopted from Xu et al., 2021)

3 Effects of Planting Density on Soybean Growth Traits

3.1 Changes in plant height and stem diameter

Planting density significantly influences soybean plant height and stem diameter, with higher densities generally promoting taller plants but thinner stems. Increased competition for light in dense populations stimulates stem elongation as plants strive to capture more sunlight, resulting in increased plant height. For example, studies have shown that soybean plants grown at higher densities exhibited greater heights compared to those at lower densities, with the tallest plants observed under intermediate to high density treatments (Ran et al., 2023; Xu et al., 2024). However, this elongation often comes at the expense of stem diameter, which tends to decrease as planting density increases due to limited resources and mechanical support constraints. Thinner stems can reduce lodging resistance, potentially affecting yield stability under adverse weather conditions (Wang et al., 2023).

The interaction between planting density and row spacing also affects these growth traits. Narrower row spacing combined with high density can exacerbate stem thinning while promoting height increase, whereas wider spacing may moderate these effects by reducing intra-specific competition. Additionally, varietal differences influence how plant height and stem diameter respond to density changes; some genotypes maintain thicker stems even at higher densities due to stronger meristem regulation (Figure 2) (Li et al., 2024). Understanding these dynamics is crucial for optimizing planting configurations that balance plant architecture traits conducive to both high yield and lodging resistance.

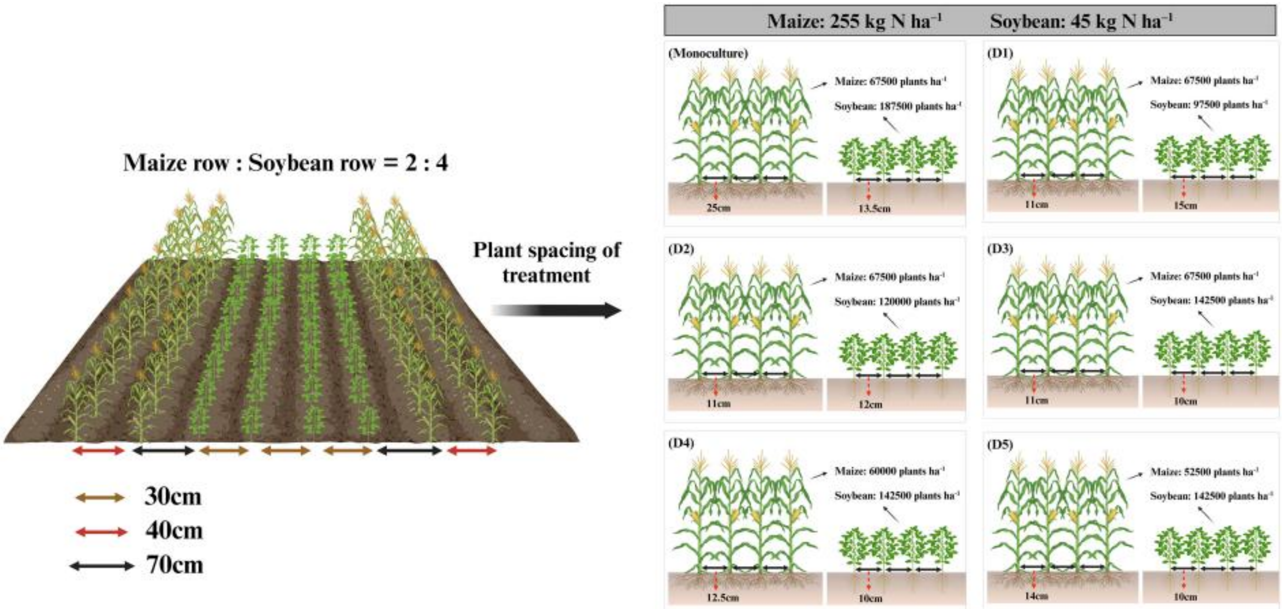

Figure 2 The diagram showing plant spacing and nitrogen input for different treatments in the field (Adopted from Li et al., 2024)

3.2 Leaf area index and canopy structure characteristics

Leaf area index (LAI), a key indicator of canopy development and photosynthetic capacity, generally increases with planting density up to an optimal point before plateauing or declining due to excessive shading and leaf senescence. Higher planting densities lead to denser canopies with greater leaf area per unit ground area, enhancing light interception during early and mid-growth stages (Zhang et al., 2011). For instance, LAI values measured at critical growth stages such as flowering (R1-R2) and pod filling (R5-R6) consistently showed positive correlations with increasing plant density within a certain range. However, very high densities may cause self-shading in the lower canopy layers, reducing overall photosynthetic efficiency (Lin et al., 2009).

Canopy structure characteristics also shift with planting density; denser populations tend to have more upright leaves and altered leaf angle distributions that affect light penetration through the canopy. Uniform plant spacing enhances canopy light interception by reducing gaps and uneven shading compared to non-uniform distributions (Xu et al., 2021). Moreover, increased density often results in reduced branch number per plant but compensates by increasing total leaf area per unit land area. These structural adjustments influence dry matter production and yield formation by modulating the balance between source capacity (photosynthesis) and sink demand (pod and seed development).

3.3 Dry matter accumulation and distribution

Dry matter accumulation in soybean populations typically follows a single-peak curve during the growing season, with accumulation rates influenced strongly by planting density. Higher densities increase total dry matter per unit area due to greater leaf area and photosynthetic activity but may reduce dry matter accumulation per individual plant because of intensified competition (Zhang et al., 2011). Studies have reported that total biomass production rises with increasing density up to an optimum level beyond which gains diminish or reverse. The distribution of dry matter among plant organs also varies; for example, dry weight tends to concentrate more in stems and leaves at early stages but shifts toward pods and seeds during reproductive phases (Mondal et al., 2014).

Dry matter partitioning patterns are affected by both density and genotype. Some varieties maintain higher proportions of assimilates allocated to reproductive organs under dense planting, supporting better yield performance (Li et al., 2022). Additionally, uniform spatial distribution enhances dry matter accumulation by improving light interception uniformity across plants (Xu et al., 2021). Understanding how dry matter accumulates and partitions under different densities helps identify optimal planting strategies that maximize biomass production while ensuring efficient resource allocation toward seed yield. Overall, these findings highlight that managing planting density is critical for optimizing soybean growth traits such as plant height, stem diameter, LAI, canopy structure, and dry matter dynamics—all of which collectively influence final yield outcomes. Balancing these factors through appropriate density selection tailored to local environmental conditions and cultivar characteristics can improve soybean productivity sustainably.

4 Effects of Planting Density on Photosynthetic Characteristics and Physiological Indices

4.1 Changes in photosynthetic rate and chlorophyll content

Planting density has a notable impact on the photosynthetic rate and chlorophyll content of soybean leaves, which are critical for biomass accumulation and yield formation. Increasing planting density generally enhances leaf area index (LAI) and canopy coverage, leading to improved light interception and photosynthesis at the population level. For example, doubling plant density from 160,000 to 320,000 plants per hectare significantly increased leaf chlorophyll content and net photosynthetic rate, contributing to higher aboveground biomass and seed yield (Liao et al., 2022). However, excessively high densities can induce shading stress within the canopy, reducing individual leaf photosynthetic capacity due to lower light availability and altered microclimate conditions.

Chlorophyll content measured by SPAD values tends to increase with planting density up to an optimal point, reflecting enhanced nitrogen status and photosynthetic pigment concentration in leaves. Studies have shown that moderate densities improve chlorophyll content during key growth stages such as flowering and pod filling, supporting sustained photosynthesis (Zhang et al., 2015). Yet, at very high densities, chlorophyll content may decline or plateau as competition for nutrients intensifies. Thus, an optimal planting density balances increased canopy photosynthesis with maintenance of leaf physiological health to maximize productivity.

4.2 Analysis of light use efficiency in the population

Light use efficiency (LUE), defined as the conversion efficiency of intercepted light into biomass or yield, is influenced by planting density through its effects on canopy structure and light distribution. Increasing density raises LAI and intercepted photosynthetically active radiation (IPAR), which generally enhances total biomass production (Liao et al., 2022). However, beyond a certain threshold, dense canopies suffer from self-shading that reduces light penetration to lower leaves, decreasing overall LUE at the population scale (Zhang et al., 2021). This decline in LUE at very high densities is linked to reduced net photosynthetic rates per leaf area despite greater total light interception.

Uniform plant spacing combined with optimal density improves canopy light interception uniformity and reduces gaps that cause inefficient light use. Research indicates that uniform distribution increases dry matter accumulation by enhancing LUE compared to non-uniform spacing under similar densities (Xu et al., 2021). Additionally, cultivars tolerant to higher densities maintain better canopy architecture that optimizes light distribution and sustains higher LUE under dense planting conditions (Zhang et al., 2021). Therefore, managing both planting density and spatial arrangement is essential for maximizing LUE in soybean populations.

4.3 Responses of key physiological indicators

Key physiological indices such as SPAD value (relative chlorophyll content), transpiration rate (Tr), stomatal conductance (Gs), and intercellular CO_2 concentration (Ci) respond dynamically to changes in planting density. Moderate increases in density often elevate SPAD values due to improved nitrogen uptake efficiency per unit land area and enhanced leaf chlorophyll synthesis (Liao et al., 2022). Transpiration rate typically shows a peak at intermediate densities corresponding with maximum stomatal conductance during critical growth stages like flowering or pod filling but declines at very high densities due to stomatal closure induced by stress factors such as shading or water limitation (Zhang et al., 2015).

Stomatal conductance follows a similar pattern; it increases initially with rising density but decreases when crowding limits gas exchange efficiency. Intercellular CO_2 concentration often decreases with increasing density up to an optimum level due to enhanced photosynthetic activity but may rise again under excessive crowding when photosynthesis is inhibited (Zhang et al., 2015). These physiological responses reflect complex interactions between environmental conditions within the canopy and plant water-nutrient status modulated by planting density. Optimizing these indices through appropriate density management supports improved gas exchange, photosynthesis, and ultimately yield.

In summary, soybean planting density influences photosynthetic characteristics and physiological indices through modifications in canopy structure, light environment, and resource competition. Moderate increases in density enhance chlorophyll content, photosynthetic rate, light use efficiency, and favorable physiological responses such as higher SPAD values and balanced transpiration rates. However, excessively high densities can lead to shading stress that diminishes these benefits by reducing individual leaf function despite greater total canopy coverage. Optimal planting strategies should therefore balance population size with spatial arrangement to maximize photosynthetic performance and physiological health for sustainable yield improvement (Figure 3) (Liao et al., 2022).

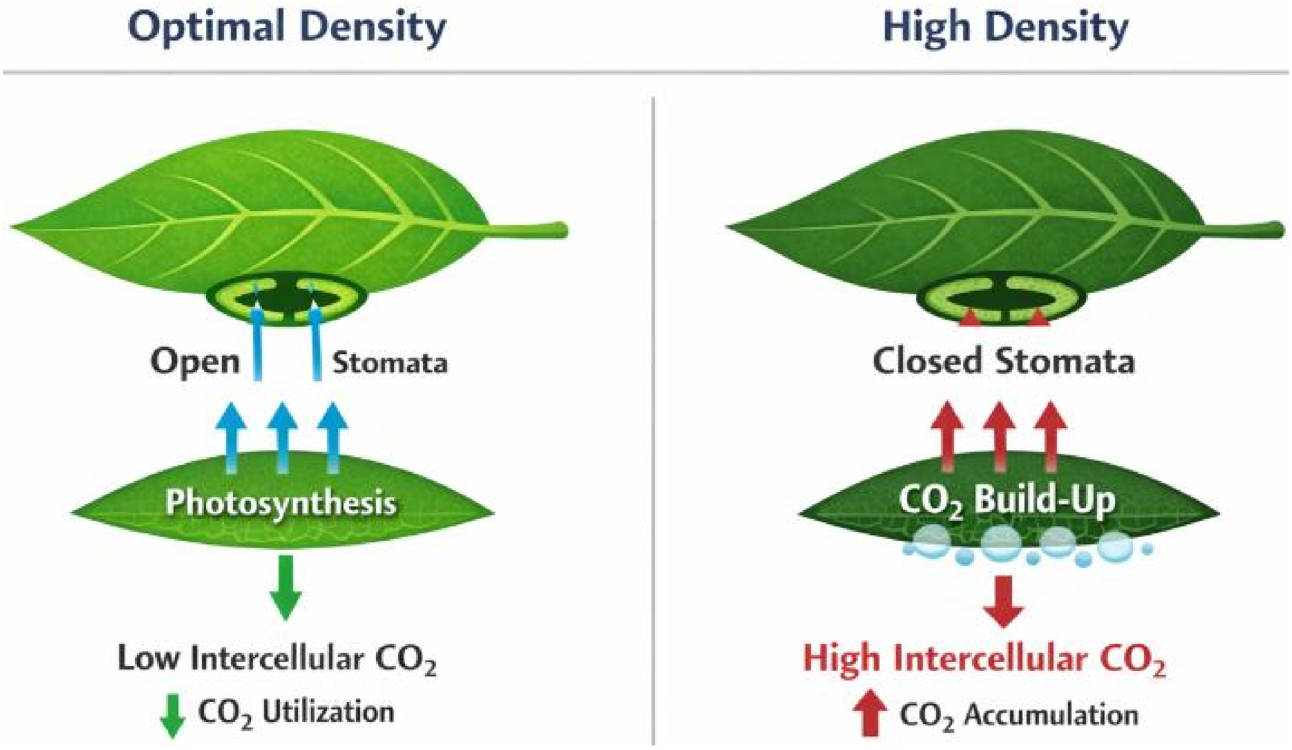

Figure 3 Schematic illustration of stomatal regulation and intercellular CO_2 dynamics under optimal and excessive planting densities (Adopted from Liao et al., 2015)

5 Effects of Planting Density on Soybean Yield and Its Components

5.1 Variations in individual plant yield and population yield

Planting density exerts contrasting effects on individual plant yield and overall population yield in soybean production. As density increases, the yield per individual plant typically decreases due to intensified competition for resources such as light, nutrients, and water. However, this reduction in per-plant productivity is often offset by a greater number of plants per unit area, leading to an increase in total population yield up to an optimal density (Yang et al., 2025). For example, research in the Huang-Huai-Hai Plain demonstrated that while individual-level relative productivity declined with increasing density, population-level seed yield peaked at around 315,000 plants per hectare, indicating that higher densities can compensate for lower individual yields through enhanced canopy development and light interception (Yang et al., 2025). Similarly, studies across North America found that low-yield environments required higher planting densities to maximize population yield compared to high-yield environments where lower densities sufficed (Carciochi et al., 2019).

The balance between individual and population yield is influenced by environmental conditions and cultivar characteristics. In high-yield environments, plants tend to produce more seeds per plant at lower densities, whereas in low-yield environments, increasing density helps maintain yield by compensating for reduced seed number per plant (Carciochi et al., 2019). Additionally, uniform spatial distribution of plants at higher densities reduces variability among individuals and improves overall yield stability (Xu et al., 2021). These findings highlight the importance of tailoring planting density to specific growing conditions to optimize both individual plant performance and total soybean productivity.

5.2 Responses of pod number, seed number, and 1000-seed weight

Yield components such as pod number per plant, seed number per pod, and 1000-seed weight respond differently to changes in planting density. Generally, increasing planting density leads to a decrease in pod number per plant due to resource competition limiting branch development and reproductive capacity (Rahman et al., 2011). However, the total number of pods per unit area may increase or remain stable because of the greater number of plants compensating for fewer pods per individual. Seed number per pod tends to be less sensitive to density changes but can decline slightly under very high densities due to stress during pod development (Yang et al., 2025).

The 1000-seed weight often decreases with increasing planting density as competition restricts assimilate availability for seed filling (Rahman et al., 2011). For instance, studies have shown that while seed weight declines at very high densities beyond 315,000 plants per hectare, moderate increases in density maintain or slightly reduce this parameter without severely impacting final yield. Cultivar differences also play a role; some genotypes maintain higher seed weights under dense planting due to better resource allocation strategies (Xu et al., 2021). Overall, optimizing planting density involves balancing these components—maximizing pod and seed numbers while minimizing reductions in seed weight—to achieve the highest possible grain yield.

5.3 Determination of optimal planting density range

Determining the optimal planting density range is critical for maximizing soybean yield while maintaining resource use efficiency. Research indicates that optimal densities vary by region, environment, cultivar, and management practices but generally fall within a moderate-to-high range. In the Huang-Huai-Hai Plain region of China, densities between 270,000 and 315,000 plants per hectare produced the highest economic returns and seed yields by balancing source-sink relationships and improving pod-setting characteristics (Yang et al., 2025). Similarly, North American studies suggest that agronomic optimal plant density (AOPD) increases from high- to low-yield environments by approximately 24%, reflecting adaptation needs based on environmental constraints (Carciochi et al., 2019).

Other investigations recommend densities around 80-100 plants per square meter (800,000-1 million plants per hectare) depending on variety and seasonality but emphasize that exceeding certain thresholds (e.g., above 315,000 plants/ha) may reduce individual plant performance without proportional gains in population yield (Rahman et al., 2011; Sacramento et al., 2020). Uniform spatial distribution combined with appropriate density further enhances light interception and dry matter accumulation leading to improved yields. Therefore, selecting an optimal planting density requires consideration of local conditions alongside cultivar traits to ensure sustainable soybean production with maximized yield potential.

6 Effects of Planting Density on Canopy Structure and Resource Use Efficiency

6.1 Changes in ventilation and light penetration within the canopy

Planting density significantly influences canopy structure, which in turn affects ventilation and light penetration-key factors for photosynthesis and crop health. Increasing planting density generally raises the leaf area index (LAI) and canopy coverage, leading to greater interception of photosynthetically active radiation (PAR). However, denser canopies often reduce light penetration to lower leaves due to self-shading, which can limit photosynthetic efficiency in the lower canopy layers (Li et al., 2024). For example, optimizing row spacing in high-density soybean plantings improved canopy transmittance by creating a more favorable light environment that enhanced photosynthetic capacity and reduced excessive shading.

Ventilation within dense canopies is also affected by planting density, as tighter spacing can restrict air movement, increasing humidity and potentially promoting disease development. Adjusting spatial arrangements such as row spacing can improve airflow and reduce microclimate stress within the canopy. Studies on maize and cotton similarly show that moderate densities optimize canopy structure to balance light interception with adequate ventilation, supporting healthier growth and yield stability (Zhang et al., 2021; Zhai et al., 2024). Thus, managing planting density alongside spatial configuration is crucial for maintaining optimal light distribution and ventilation in soybean canopies.

6.2 Water and nutrient use efficiency

Water use efficiency (WUE) and nutrient use efficiency (NUE) are closely linked to planting density through their effects on root competition, canopy transpiration, and nutrient uptake dynamics. Moderate increases in planting density enhance resource capture by increasing total leaf area and root volume per unit land area, thereby improving precipitation use efficiency (PUE) and NUE up to an optimal point (Figure 4) (Duan et al., 2025). However, excessively high densities may reduce individual plant access to water and nutrients due to intensified competition, leading to diminished WUE and NUE despite higher total biomass production (Zhang et al., 2021).

Research in semiarid environments indicates that moderate planting densities combined with density-tolerant cultivars achieve better balance between resource uptake and utilization efficiency than very high densities (Zhang et al., 2021). Similarly, studies on cotton demonstrate that increased planting density improves nutrient uptake correlated with higher leaf area index but only up to a threshold beyond which efficiency gains plateau or decline (Zhai et al., 2024). In soybean, uniform plant distribution at higher densities enhances dry matter accumulation without additional inputs by optimizing resource use across the population (Xu et al., 2021). Therefore, careful management of planting density is essential for maximizing water and nutrient use efficiencies while avoiding detrimental competition effects.

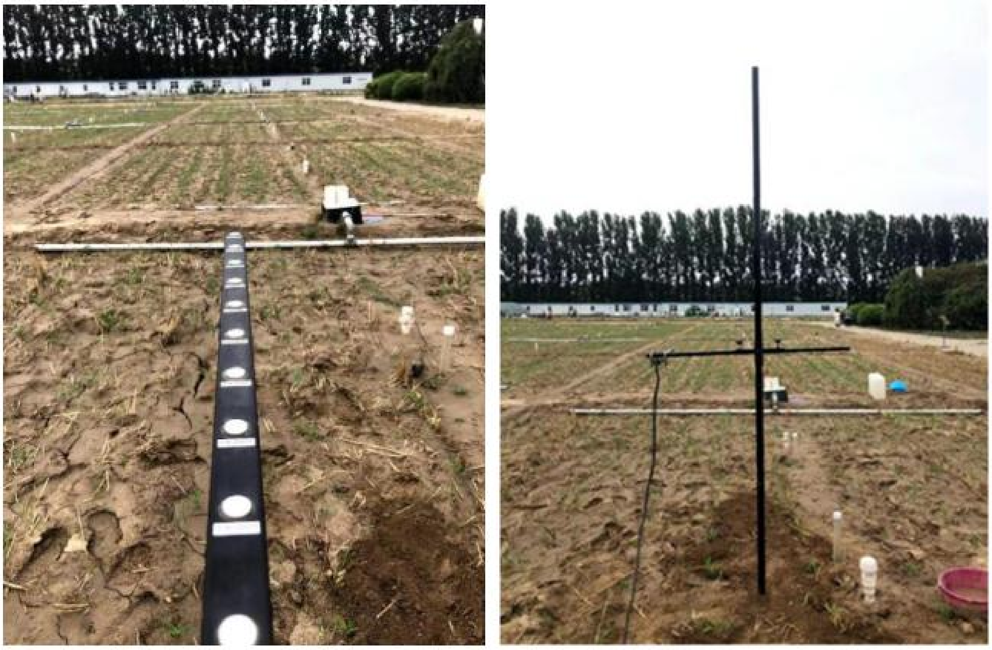

Figure 4 AV-19LQ total solar radiation sensor (Adopted from Duan et al., 2025)

6.3 Regulation of intraspecific competition under different densities

Intraspecific competition among soybean plants intensifies with increasing planting density as individuals compete for limited resources such as light, water, and nutrients. This competition affects plant growth plasticity, architecture, nitrogen accumulation, and ultimately yield potential (Klimek-Kopyra et al., 2020). Studies show that low to moderate densities reduce competitive stress allowing plants to express their productive potential fully; however, at very high densities or under favorable moisture conditions, strong competition can limit individual performance despite increased population size (Klimek-Kopyra et al., 2020). For instance, rainfall variability modulates the intensity of intraspecific competition—higher rainfall increases competition severity while drought reduces it by limiting overall growth (Klimek-Kopyra et al., 2020).

Spatial arrangement also plays a role in regulating competition; uniform plant spacing reduces variability among individuals by minimizing dominance hierarchies within the canopy (Xu et al., 2021). Variable-density row arrangements have been tested but did not consistently improve yield over uniform high-density plantings in soybean (Ethridge et al., 2022). Optimizing both planting density and spatial distribution helps mitigate negative effects of intraspecific competition by balancing resource availability with population size. This regulation supports improved growth uniformity, physiological function, and yield stability across diverse environmental conditions.

7 Discussion

7.1 Mechanisms of differences in growth and yield under different densities

Differences in soybean growth and yield under varying planting densities are primarily driven by changes in resource availability and plant physiological responses. Higher planting densities increase leaf area index (LAI) and aboveground biomass, which enhance light interception and photosynthetic capacity, ultimately boosting seed yield (Liao et al., 2022). However, increased density also intensifies competition among plants for water, nutrients, and light, which can reduce individual plant growth and seed size despite higher population yields (Liao et al., 2022; Xu et al., 2021). For example, at very high densities, soybean plants may exhibit reduced branch number and smaller stem diameter due to shading and resource limitations, affecting lodging resistance and yield stability (Xu et al., 2021; Xu et al., 2024).

Physiological mechanisms such as chlorophyll content, photosynthetic rate, and root growth are also influenced by density. Increased density combined with adequate nitrogen fertilization and supplemental irrigation improves these parameters, enhancing water-nitrogen use efficiency and biomass accumulation (Liao et al., 2022). Conversely, excessive density without balanced nutrient or water supply can exacerbate stress conditions leading to diminished photosynthetic performance and yield penalties (Wang et al., 2023). Thus, the interplay between planting density and environmental factors regulates growth dynamics through both above- and below-ground processes that determine final yield outcomes.

7.2 Comparison with previous studies and interpretation

The findings align with previous research demonstrating that moderate to high planting densities generally improve soybean yield by optimizing canopy light interception and dry matter accumulation (Xu et al., 2021; Carciochi et al., 2019). Uniform plant distribution at higher densities reduces variability among individual plants, contributing to more stable yields compared to non-uniform spacing (Xu et al., 2021). Additionally, the optimal agronomic plant density varies by environment; low-yield environments require higher densities than high-yield environments to maximize productivity (Carciochi et al., 2019). This variation reflects differences in resource availability and climatic conditions influencing plant competition intensity.

Comparisons with intercropping systems reveal that shading stress from neighboring crops can reduce soybean stem lignin accumulation and lodging resistance at high densities, highlighting the importance of density management in mixed cropping scenarios (Wang et al., 2023). Moreover, cultivar-specific traits such as branching capacity affect how soybeans respond to density changes; cultivars with fewer branches tend to perform better under close planting due to higher tolerance of crowding. These insights emphasize the need for integrated management considering genotype-environment interactions when determining optimal planting densities.

7.3 Limitations of this study and future improvements

This study’s limitations include its focus on a limited range of planting densities and environmental conditions, which may restrict the generalizability of results across diverse agroecosystems. The interaction effects of planting density with other agronomic factors such as row spacing, sowing date, and cultivar selection were not fully explored but are known to influence canopy structure and yield components significantly (Ran et al., 2023).

Additionally, temporal variability in plant emergence was not addressed; previous work suggests that non-uniform emergence timing can negatively impact yield even at optimal densities (Masino et al., 2018).

Future research should incorporate broader environmental gradients and multiple genotypes to better understand how planting density interacts with genetic traits under variable climatic conditions. Investigating the combined effects of spatial distribution uniformity, nutrient management, irrigation regimes, and intercropping practices will provide more comprehensive recommendations for sustainable soybean production. Advanced modeling approaches integrating physiological parameters could also improve predictions of optimal density ranges tailored to specific regions. Addressing these gaps will enhance precision agriculture strategies aimed at maximizing soybean growth efficiency and yield stability.

8 Conclusions and Recommendations

This study confirms that planting density plays a critical role in determining soybean growth, canopy structure, resource use efficiency, and ultimately yield. Increasing planting density generally enhances leaf area index, dry matter accumulation, and canopy light interception, which contribute to higher seed yields under optimal conditions. However, excessively high densities can intensify intraspecific competition for light, water, and nutrients, leading to reduced individual plant performance and potential yield penalties if not managed properly. Uniform plant distribution combined with moderate to high densities improves population uniformity and reduces variability in seed weight among plants, further boosting overall yield. Additionally, environmental factors such as water availability and nitrogen supply interact with planting density to influence photosynthetic capacity and biomass production. These findings highlight the complex balance between maximizing population size and minimizing competition stress to optimize soybean productivity.

Optimal planting density varies depending on environmental conditions, cultivar traits, and management practices. In general, densities around 180,000 to 270,000 plants per hectare are recommended for achieving high yields in favorable environments when combined with uniform spacing and adequate nutrient and water supply. For example, a 20-60 cm row spacing configuration at high density improved canopy light environment and photosynthetic efficiency, resulting in yield increases of up to 5.9% compared to equidistant planting. In lower-yield or stress-prone environments, higher densities may be necessary to compensate for reduced individual plant performance. Cultivar selection also matters; varieties with fewer branches tend to perform better under close planting due to greater tolerance of crowding. Practical implications include adopting uniform plant spacing techniques and adjusting row configurations to optimize light penetration while avoiding excessive competition that can reduce lodging resistance or increase disease risk.

Future research should explore broader environmental gradients and genotype-by-environment interactions to refine optimal planting density recommendations across diverse agroecosystems. Investigations into the combined effects of spatial distribution uniformity, nutrient management strategies (including nitrogen rates), irrigation regimes, and intercropping systems will provide more holistic insights into sustainable soybean production. Additionally, studies on the role of plant growth regulators like DA-6 in mitigating high-density stress show promise for enhancing branching architecture and yield under dense planting conditions. Incorporating advanced modeling approaches that integrate physiological parameters could improve prediction accuracy for site-specific density optimization. From an agricultural practice perspective, promoting precision planting technologies that ensure uniform spacing alongside tailored nutrient and water management will be key to maximizing soybean growth efficiency and yield stability.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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