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Effects of Different Sowing Densities on Soybean Yield and Quality

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Abstract Soybean (*Glycine max*) is a vital global crop valued for its protein and oil content, making the optimization of agronomic practices such as sowing density essential for improving both yield and quality. This study synthesized the current research results on the physiological, environmental and genotypic effects of different sowing densities on soybean growth and development, and explored how plant competition for resources, canopy structure and root development interact with sowing density to affect yield and seed quality traits such as protein and oil content, uniformity and vitality; further explored how environmental factors such as soil fertility, climate change and management practices regulate density response, and the differences in genotype adaptability to high-density and low-density planting. The case study in China provides localized insights for the practical application of optimizing sowing density, while future development directions emphasize the application of precision agriculture and remote sensing technology integration in density management. This study underscores the need for site- and variety-specific sowing strategies to enhance sustainable soybean production and guide future agronomic innovations.

Keywords Soybean yield; Sowing density; Seed quality; Plant physiology; Precision agriculture

1 Introduction

Soybean (*Glycine max*) is an important crop worldwide. It is rich in protein and oil, and can be used not only as food, but also as feed and industrial raw materials, so it has many uses. This crop can adapt to various climates and can also help agricultural sustainable development through nitrogen fixation, so it plays a very important role in ensuring global food security and agricultural development (Claupein et al., 2019; Jańczak-Pieniążek et al., 2021).

In order to improve the yield and quality of soybeans, it is particularly important to improve planting technology, among which sowing density is a key factor. Sparse or dense planting will affect plant morphology, growth effect, yield structure and resource utilization efficiency, such as competition for light, water and nutrients (Schmidt et al., 2019; Guo et al., 2022). The right sowing density helps to form a better canopy structure, and also allows photosynthesis and rhizobium activity to be smoother, while reducing negative situations such as lodging or reduced pod number (Ball et al., 2001; Huang et al., 2024). Because conditions vary from place to place and from management to management, each region needs to adjust the sowing density according to the actual situation in order to obtain the best yield and quality (Strunjaš et al., 2010).

The main purpose of this study is to summarize the current research results on the changes in soybean yield and quality under different sowing densities. We will explore the effects of different planting densities on yield components, seed components (such as protein and oil content), plant appearance and physiological processes, which will vary depending on environmental and management conditions. In addition, we will focus on analyzing the relationship between sowing density and other planting factors, and finally put forward some practical suggestions to help improve soybean yield and quality worldwide.

2 Theoretical Basis of Sowing Density and Plant Physiology

2.1 Plant competition for light, nutrients, and water

When the sowing density increases, the competition between plants for light, nutrients and water will also increase.

The higher the density, the taller the stems will grow in order to compete for light, and the area of leaves or cotyledons may decrease (Henry et al., 2019). Although the individual quality of each plant may decrease, the overall yield may still increase because there are more plants in the field (Daşgan and Balik, 2025; Filho et al., 2025). However, if the competition is too intense, the chlorophyll in the leaves may decrease, the vitality of the seeds will also weaken, and finally affect the yield and quality (Zucareli et al., 2021).

2.2 Influence on canopy structure and microclimate

Planting density directly affects the structure of the crop canopy, which in turn affects the microclimate in the field (Figure 1). Generally speaking, high density makes the canopy thicker, so that sunlight cannot easily reach the leaves below, relative humidity will increase, and the temperature and carbon dioxide concentration in the canopy will decrease (Wu et al., 2023). These changes will affect the photosynthetic efficiency of the plant, the degree of leaf cover, and the distribution of nutrients, which may affect the effect of grain filling and yield performance (Bobrecka-Jamro et al., 2023; Błaszczyk et al., 2024). Therefore, in order to make the crop grow healthily and have high yields, the density must be selected to ensure that light can penetrate, air can circulate, and the humidity is not too high.

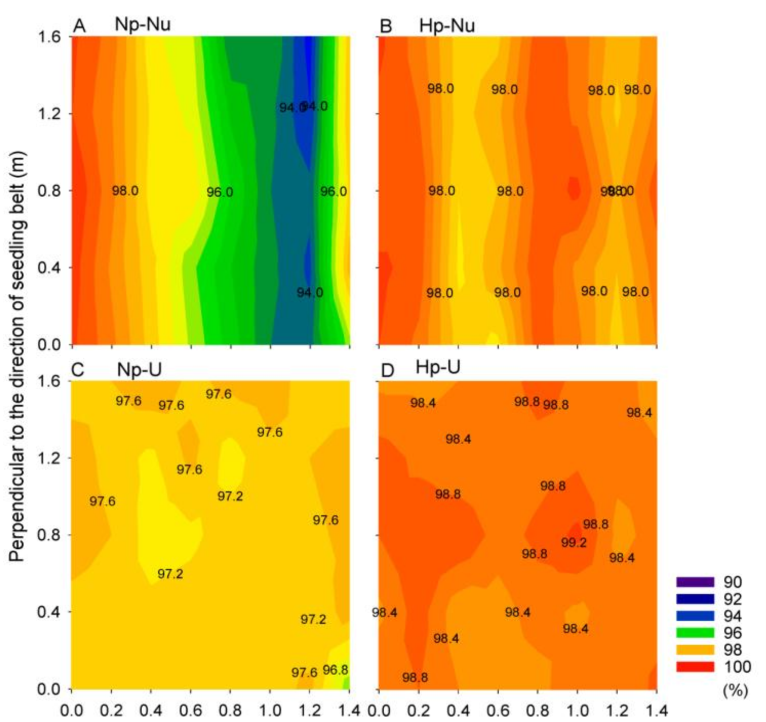

Figure 1 Effect of plant distribution on canopy light interception rate of soybean under different planting densities. (A-D), the canopy light interception rate under Np-Nu, Hp-Nu, Np-U, and Hp-U treatments, respectively. Np, normal seeding density. Hp, high seeding density. Nu, non-uniform plant distribution. U, uniform plant distribution. The change from dark blue to deep red indicates that the canopy light interception rate gradually increases. The number represents the value of canopy light interception rate on the contour line (Adopted from Xu et al., 2021)

2.3 Root development and its effect on nutrient uptake

Seeding density also affects how the roots of plants grow. When the density is relatively high, the roots in the topsoil will be more numerous and denser, because the plants will grow more fine roots, which can more effectively absorb nutrients from the upper soil (Temperton et al., 2016). However, due to increased competition, plants will use more resources on the aboveground part, which may reduce the root system ratio and cause the roots to grow deeper (Rascher et al., 2018). In addition, the number of nodal roots and the unit root length will also change, which will affect the efficiency of water and nutrient absorption. Understanding the response of these roots is very helpful for breeding and field management, especially in different seeding densities, which can better improve yields.

3 Impact of Sowing Density on Soybean Yield

3.1 High-density sowing and its yield advantages and trade-offs

When the planting is denser, the space between rows will become smaller, the leaves will cover more fully, the leaf area index will be higher, and light and nutrients can be used more thoroughly, so the total yield per acre can often be increased (Claupein et al., 2019). Experiments have found that when the density is high, the plants will grow taller and the first pod will be higher from the ground. This is especially true in plots with low yields or in systems where they are intercropped with other crops (Muguerza et al., 2023). However, the benefits come with costs: the number of pods and branches that can be grown per plant will decrease, the number of nodules and root dry weight will decrease, and the number of seeds per plant and overall vitality may also decrease (Guo et al., 2022a). Too high a density will also make the competition for water and fertilizer more intense, the quality of grains may decline, and the risk of lodging will increase.

3.2 Low-density planting and its role in resource use efficiency

If the row spacing is widened and the plant spacing is enlarged, there will be less competition between plants, and each plant can grow more branches and pods, and more nutrients can be invested in root growth and nodule formation (Jańczak-Pieniążek et al., 2021). In high-yield areas with good conditions, this method can make up for the reduction in the number of plants by increasing the yield per plant, and resource utilization can be maintained or improved (Bittencourt et al., 2022). However, if the number of plants is so low that the sunlight and water and fertilizer in the soil are not fully used, especially in less than ideal environments, the total yield may drop. Low density also often improves some physiological indicators, such as chlorophyll fluorescence and root health, thereby improving grain quality.

3.3 Optimal density for maximizing yield under different climatic conditions

The planting density that can maximize yield will vary depending on the local climate, soil, and management practices. In low-yield areas, higher density is required to achieve the highest yield; in high-yield areas, relatively lower density can be used because individual plants can make up for the yield by setting more seeds (Pospišil and Pospišil, 2024). For example, research in North America indicates that the agronomically optimal planting density increases by about 24% from high-yield to low-yield areas (Schmidt et al., 2019). In Northeast China, the density that can achieve the highest yield is about 45.4×10^4 plants/hectare (Wang et al., 2023). In areas with short growing seasons and low temperatures, early planting and medium density can often adjust the canopy structure and drive yield increases (Huang et al., 2024). Therefore, the planting density must be adjusted according to the local climate and management conditions to optimize both yield and resource utilization (Ball et al., 2001).

4 Influence of Sowing Density on Seed Quality

4.1 Effects on protein and oil content of seeds

Whether the density of planting is high or low will directly affect the nutritional content of the seeds. For example, in the case of crambe, high density will increase the crude fat (oil) and crude fiber content, but the total protein will decrease (Szatkowski et al., 2024). A similar phenomenon also occurs in peas: when the density is increased from 70 plants per square meter to 110 plants per square meter, the protein content in the seeds will also increase (Bobrecka-Jamro et al., 2023). These results show that oil is more likely to accumulate at high density, but the protein ratio may be diluted; the specific changes depend on the local climate and variety characteristics.

4.2 Relationship between plant spacing and seed uniformity

Plant spacing, row spacing and density are tied together to determine whether the seed size is uniform. For white lupin, wider row spacing and lower density will result in more chlorophyll in the leaves and heavier seeds per plant, indicating that the conditions between plants are loose and the grains develop more evenly (Jańczak-Pieniążek et al., 2023). If the density is too high, the plants will compete more fiercely for light and fertilizer, and the nutrients will be unevenly distributed, which will easily lead to a widening gap in seed size and quality.

4.3 Sowing density and its impact on seed viability and germination

Density also affects the vitality and germination of seeds in the later stage. Wheat experiments show that high density can increase the total yield, but it will reduce seed vitality and germination rate, which is more obvious in varieties with high vitality (Zucareli et al., 2021). The results of rapeseed are similar: when the density is set in a moderate range, the survival rate of seedlings is high and the agronomic traits are good; when the density is increased, the quality of seedlings decreases, and the survival rate after transplanting is also low (Zuo et al., 2022). Therefore, in order to maintain high seed vitality and high germination, the sowing density must be stuck in an appropriate range, neither wasting resources nor adding burden to the seedlings.

5 Interaction with Environmental and Agronomic Factors

5.1 Role of soil fertility and irrigation practices

The quality of the soil and the amount of water will directly affect the effect of sowing density. Sowing density, soil type and fertilization method will affect each other, and the impact on quality is often greater than the impact on yield. To achieve high yields, it depends on the proper combination of soil and climatic conditions in specific areas (Cammarano and De Santis, 2024). How much rain and whether there are enough water resources, especially during the critical period of crop growth, are key factors in determining high-density or low-density yield performance (Mumford et al., 2023). For example, the amount of nitrogen fertilizer and when it is applied will interact with density and work together on yield and quality. Therefore, in order to increase yield, water and fertilizer management cannot be considered separately, but must be combined together.

5.2 Influence of climate zones and seasonal variation

Climate conditions, such as temperature, rain and sunshine, are the most important external factors affecting the performance of planting density (Arif et al., 2023). Seasonal changes can also make a big difference. Some varieties or management methods work better in certain weather conditions (Nsarellah et al., 2024). For example, if the climate is mild and water is sufficient, it may be easier to get high yields by planting densely; but in places with dry and hot weather and prone to water shortages, too high a density may not be as good as planting sparsely (Howard et al., 2017). The relationship between density, variety, climate and management measures is very complex. Many studies now use predictive models to take environmental parameters into account to help determine which density is appropriate in what season and climate conditions.

5.3 Integration with other agronomic practices such as fertilization and pest control

Density cannot be determined alone. It must be considered together with management measures such as fertilizer use and pest and disease control to ensure stable production and quality. In particular, nitrogen fertilizer application has a strong linkage with density, which not only affects yield but also has an impact on the environment. The amount of fertilizer and the time of fertilization are the most influential pair of matching factors (Van Eeuwijk et al., 2001). Pest and disease control measures will also interact with density. Sometimes high density makes pests and diseases more likely to occur; but this is not necessarily the case, depending on the crop type and local conditions (Schulzova et al., 2023). Therefore, in actual production, it is best to combine density, fertilization and pest and disease control according to the specific situation and formulate a suitable management plan. This will maximize yield while minimizing the impact on the environment.

6 Genotypic Response to Sowing Density

6.1 Variation in density response among different soybean cultivars

Different varieties of soybeans perform very differently when they encounter high density. Field and indoor experiments have found that the three types of genotypes - determinate, semi-determinate and indeterminate - will increase biomass and grain yield per mu when the density is high, but the increase is different. For example, if the density of the determinate "Wuyin No. 9" is doubled, its yield can be increased by 93%; the semi-determinate "You 91-19" only increases by 37%, and the indeterminate "Jufeng" increases by 43%. However, under high density, the biomass and grain weight of the determinate plant are not greatly affected, while the weight of the late-maturing indeterminate plant drops sharply (Stulen et al., 2002). This shows that choosing the right genotype is critical to getting high yields at a specific density.

6.2 Genetic traits associated with high-density adaptability

Varieties that can produce stable yields at high density usually have some special physiological and morphological characteristics. Their leaf area ratio (LAR) and specific leaf area (SLA) tend to remain stable or even higher, and their nitrogen fixation efficiency is also good. The yield of a limited-growth plant is less affected by crowding; because the unlimited-growth plant competes more fiercely for light and fertilizer, the biomass and grain weight of a single plant decrease more. These phenomena show that in order to make soybeans suitable for high density, we must rely on traits that can efficiently utilize resources and are less sensitive to crowding.

6.3 Breeding considerations for density-tolerant varieties

When breeding density-tolerant soybeans, we should look for genotypes that can produce stable yields at different densities, especially those with limited or semi-limited growth, because they do not drop much per plant yield under crowded conditions. We should focus on several physiological indicators: appropriate LAR, SLA, and strong N_2 fixation ability. If these characteristics are integrated into the breeding program, new varieties that do not sacrifice seed quality and have strong plants at high density can be cultivated, so that soybean cultivation can continue to develop in an intensive and sustainable direction.

7 Case Study: Application in China

7.1 Background: local climate, soil type, and soybean farming practices

The main soybean growing areas in China are Northeast China and Southern Xinjiang, where the climate and soil conditions are quite different. Northeast China has fertile black soil and a relatively mild climate, making it one of the most important soybean growing areas in my country (Guo et al., 2022b). In Southern Xinjiang, the growing season is short, and soybeans and winter wheat are often planted in rotation, which requires more careful arrangement of sowing time and density to get a good yield. At present, the planting methods in many places are still determined by farmers' experience, not relying on data analysis, which makes the sowing density and input level vary significantly in different places.

7.2 Trial results of different sowing densities on local soybean cultivars

In the Northeast, Heihe No. 43 was used as the test material. The test found that on the basis of applying a certain amount of fertilizer, the yield was the highest when 45.37×10^4 plants/hectare were planted, reaching 3816.67 kg/hectare. In East China, five varieties participated in the test and found that as the density increased, the yield also increased, but when the density exceeded 160,000-180,000 plants/hectare (the specific figures vary slightly depending on the variety), the yield declined due to fierce competition (Han et al., 2021). In southern Xinjiang, the test results showed that early sowing with low density (for example, 206,800 plants/hectare) can achieve the best results, with the highest yield and a more reasonable canopy structure; while late sowing with high density, the plants grow tall and thin, and the yield is reduced (Figure 2). These experiments show that the sowing density must be matched with the local variety characteristics and environmental conditions, and cannot be a one-size-fits-all approach.

7.3 Lessons learned and recommendations for scalable implementation

The optimal density for each place and variety is different. If you want to get high yields, you have to give localized suggestions based on local conditions (Huang et al., 2024). If the appropriate density can be matched with the amount of fertilizer and sowing time, the yield will be significantly improved, and the yield difference between regions can be narrowed (Wang et al., 2023). The current management method should gradually shift from "relying on experience" to "relying on data", and more accurate planting suggestions can be obtained through simulation software and field trials, so that resource utilization is more efficient. As long as the climate, soil and variety reactions of various places are fully considered, these density optimization and supporting measures can be extended to all soybean producing areas across the country. These research results provide a basis for formulating soybean planting strategies suitable for different regions. By scientifically arranging sowing density and agronomic management, the yield and quality of soybeans in my country can be further improved.

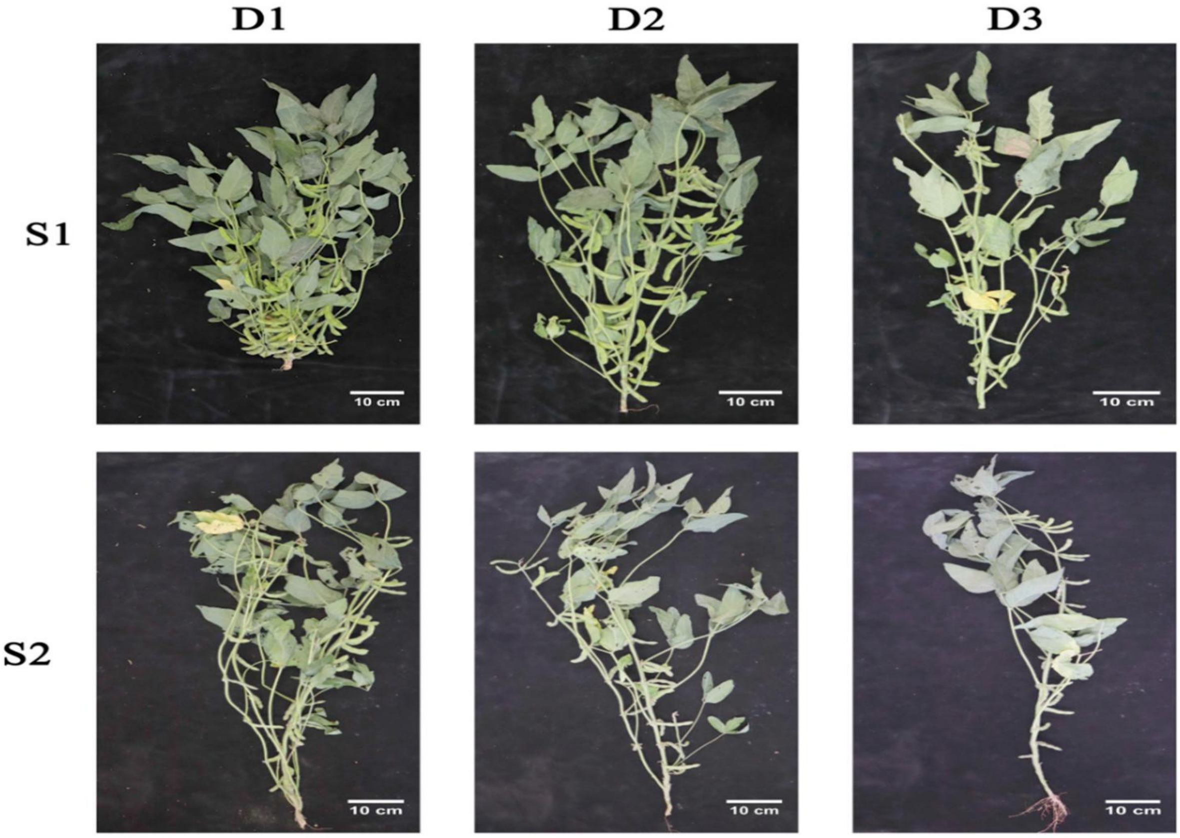

Figure 2 Growth of single spring soybean plants at the full seed (R6) stage (Adopted from Huang et al., 2024)

Image caption: S1: April 7; S2: May 7; D1: 206,800 plants/ha; D2: 308,600 plants/ha; D3: 510,200 plants/ha (Adapted from Huang et al., 2024)

8 Future Directions

8.1 Precision agriculture tools for optimizing sowing density

There are many new precision agriculture equipment that are changing the way seeding density is adjusted. Automated robots, smart seed meters, and various sensor systems can accurately place seeds one by one, and can also change the seeding rate while sowing, and even automatically re-sow when missing points are found. This not only saves materials and waste, but also increases yields (Naik et al., 2016). Some battery-powered robotic seeders can also ensure that each seed is spaced uniformly and at the right depth to adapt to different crops and plot environments, while keeping labor costs to a minimum (Victor et al., 2024).

8.2 Incorporating remote sensing and modeling for field-level recommendations

Remote sensing technology combined with "precision field trials" (OFPE) is increasingly used to provide farmers with spatially coordinated sowing density recommendations. By combining satellite imagery, yield response models, and field management data, the system can automatically adjust the sowing rate based on changes in different small areas, while taking into account soil differences and time dynamics, to maximize yields and returns (Maxwell and Loewen, 2024). More advanced image analysis and modeling will also allow farmers to monitor field conditions in real time and fine-tune sowing strategies at any time, further improving accuracy and effectiveness (Li and Li, 2022; Thite and Prakash, 2025).

8.3 Policy support and farmer training for adaptive density management

Realizing the benefits of precision seeding requires government policies and farmer training. Policies that encourage the use of precision agriculture equipment and provide incentives for technology integration can accelerate the transition from "rule of thumb" to "data-based" agriculture. Training courses on automated equipment, remote sensing, and adaptive management techniques can help farmers learn to use new tools to determine appropriate seeding density, thereby increasing yields, saving resources, and making cultivation more sustainable (Aggarwal et al., 2024).

9 Concluding Remarks

Studies have generally found that sowing density has a large, complex, and environmentally dependent effect on soybean yield and quality. At high density, plants grow taller, their leaf area index increases, and seed protein content may rise; but the number of pods, branches, and nodules per plant often decreases. The yield response to density is greatly affected by weather and local climate, and in many cases climate factors are more critical than density itself. Different varieties and maturity stages also respond differently to density, so the optimal density varies with region and management.

There is no one-size-fits-all measure for optimal sowing density: it varies by region, cropping system, and soybean variety. For example, in southern Xinjiang, where the growing season is short, early sowing with low density yields the highest yields; in low-yield environments, higher density is needed to push yields up. Some varieties, such as ES Mentor, perform best at medium density, which means that recommendations must be tailored to the site and the variety. Combining crop models with field trials can more accurately identify the best combination for each environment and each genotype.

To promote sustainable soybean production, precise sowing density management is needed, taking into account local climate, soil conditions, and production goals. Density protocols tailored to specific locations and varieties, supported by models, field trials, and flexible management, can improve yield and quality while reducing resource consumption and environmental pressures. Continued research and farmer training are also important to help promote these refined strategies and ensure consistent production of high-quality soybeans in different agroecologies.

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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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