Legume Genomics and Genetics 2025, Vol.16, No.6, 253-269
http://cropscipublisher.com/index.php/lgg

Case study Open Access

Study on Optimizing Density Planting and Fertilization Strategies to Increase Bean Yield

Yuping Huang, Yunxia Chen, Hangming Lin

Tropical Legume Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China

Corresponding email: hangming.lin@hitar.org

Legume Genomics and Genetics, 2025 Vol.16, No.6 doi: 10.5376/lgg.2025.16.0026

Received: 05 Sep., 2025

Accepted: 22 Oct., 2025

Published: 05 Nov., 2025

Preferred citation for this article:

Huang Y.P., Chen Y.X., and Lin H.M., 2025, Study on optimizing density planting and fertilization strategies to increase bean yield, Legume Genomics and Genetics, 16(6): 253-269 (doi: 10.5376/lgg.2025.16.0026)

Abstract Legumes play an important role in ensuring food security and promoting sustainable agricultural development. As key agronomic measures to increase legume yields, dense planting and fertilization management have attracted increasing attention for their optimal combination. Based on field trials of various legumes and recent research results, this study systematically explored the effects of different dense planting levels on plant morphology, population structure and yield composition, analyzed the regulatory mechanisms of nitrogen, phosphorus and potassium ratios, organic and inorganic fertilizer synergy and topdressing timing on nutrient absorption and nitrogen fixation efficiency, and further discussed the effects of the interactive effects of dense planting and fertilization on biomass accumulation and resource allocation. Through regional trials in Zhumadian, Henan and Qiqihar, Heilongjiang, this study clarified the yield potential and economic benefits of the "medium-high density + nitrogen reduction and potassium increase" and "medium density + controlled-release fertilizer" models, providing a theoretical basis and practical path for achieving regionalized precision management and green and high-yield legume cultivation, which will help improve China's legume self-sufficiency level and promote the green transformation of agriculture.

Keywords Legume crops; Close planting; Nutrient management; Nitrogen fixation; Organic and inorganic fertilizers; High-yield cultivation

1 Introduction

Legumes play a dual role in global agriculture, both in terms of food supply and soil health maintenance. On the one hand, legume seeds are rich in plant protein and oil, and are an important food source for humans and livestock; on the other hand, legumes and rhizobia symbiotically fix nitrogen, fixing a large amount of nitrogen for agricultural ecosystems every year, thereby reducing dependence on fertilizer nitrogen. This biological nitrogen fixation not only meets most of the nitrogen needs of legumes for their own growth (it is estimated that 50%-60% of the required nitrogen can be provided), but also increases soil nitrogen reserves by returning stubble to the fields, improving the growth of subsequent crops. Therefore, in the context of advocating sustainable agriculture and nutritional security today, expanding legume cultivation is of great significance. The United Nations designated 2016 as the "International Year of Legumes", emphasizing the important contribution of legumes to healthy diets and soil environment (Yanni et al., 2023). At present, the total output of legumes (such as soybeans, peas, lentils, chickpeas, etc.) in the world continues to grow, but the regional distribution is uneven and the self-sufficiency rate varies greatly. For example, my country is the world's largest soybean consumer, but it is heavily dependent on imports, with a self-sufficiency rate of less than 20% (Hao et al., 2023). Improving the yield level of beans and improving soil fertility to achieve increased production and efficiency are key issues for ensuring food security and achieving sustainable agricultural development.

Under the conditions of limited arable land resources, it is an inevitable choice to tap the potential for crop yield increase by optimizing agronomic measures. Among them, reasonable dense planting and scientific fertilization management are recognized as two important means to increase crop yield and resource utilization efficiency. Appropriately increasing the planting density can increase the group light energy interception and land utilization rate, increase the biomass and pod number per unit area, and thus increase the total yield. For example, in field experiments in Northeast China, as the soybean planting density increased, the group photosynthetic light interception rate and dry matter accumulation increased significantly, and the yield per unit area increased by 22.8% compared with the conventional density (Xu et al., 2021). Higher planting density is often used in high-yield practices: for example, Xinjiang once created a soybean yield record of 6,803 kg/hectare with a density of 300,000 plants per hectare. However, overcrowding may also lead to increased competition for nutrients and light, leggy plants, and increased risk of disease, so it is necessary to accurately grasp the critical balance point between density and yield. In terms of fertilization management, the unique nitrogen fixation ability of legumes determines that their demand for nitrogen fertilizer is different from that of cereals, but nutrients such as phosphorus and potassium are also essential for their growth, development and high yield. Studies have shown that the appropriate application of nitrogen, phosphorus and potassium compound fertilizers on soils with insufficient fertility can increase soybean yields by 5%-18% (Li et al., 2024). At the same time, China has long had problems with high fertilizer input and low utilization rate, and about 40% of fertilizer nutrients are not absorbed by crops and are lost. Excessive fertilization not only pushes up production costs, but also leads to soil compaction and environmental pollution, which is contrary to the goal of green agricultural development. Therefore, it is of great practical significance for high-yield cultivation of legumes to improve fertilizer utilization efficiency by optimizing fertilization structure and dosage, and to achieve fertilizer reduction without reducing production. There is also a significant interaction between the two factors of dense planting and fertilization: reasonable fertilization can alleviate the nutrient competition caused by dense planting and improve the group productivity; accordingly, appropriate planting density can give full play to the fertilizer benefits and avoid nutrient waste.

Based on the field test results and literature reports on beans (mainly soybeans) at home and abroad in the past five years, this study systematically analyzes the impact mechanism of planting density and fertilization measures on crop growth, physiology and yield formation, focusing on the interaction and synergistic regulation effect between the two, and selects representative bean planting areas in the north and south (Zhumadian City, Henan Province and Qiqihar City, Heilongjiang Province) to carry out field experiments to verify the yield-increasing effect and applicability of dense planting and fertilization optimization strategies. By summarizing practical cases and farmer feedback from different regions, this study evaluates the agronomic and economic benefits of these technologies, and analyzes their feasibility of promotion and application in a larger area, providing theoretical basis and practical guidance for regionalized precision management and green high-yield cultivation of bean crops, and expects to contribute to improving China's bean self-sufficiency level, ensuring food security and promoting sustainable agricultural development.

2 Effects of Density on Growth and Yield

2.1 Changes in plant morphology

The response of plant morphology to the environment directly affects photosynthetic efficiency and yield formation. Under dense planting conditions, legume crops often show a typical shade escape response: individuals quickly lengthen plant height and petioles in order to compete for light, stems become thinner, and the number of branches decreases. The experiment observed that the average plant height of soybeans under high density treatment increased by about 8.2% compared with conventional density; at the same time, due to limited space resources, the number of branches per plant decreased significantly, with a decrease of more than 40%. Fan et al. (2017) pointed out that under intercropping shading conditions, the functional leaves of soybeans became smaller and the stomatal density decreased, suggesting that the closure of the population caused by high-density planting may also inhibit leaf expansion and reduce the total leaf area of a single plant. However, due to the increase in the number of plants, the leaf area index (LAI) of high-density populations is often higher than that of low-density populations, especially in the middle and late stages of growth. In terms of canopy structure, dense planting can form a more closed canopy, which improves the interception of light by the upper leaf layer, but also leads to insufficient light and poor ventilation for the lower leaves. This change in the vertical structure of the canopy needs to be optimized through variety plant type and planting method. For example, a uniform and reasonable plant spacing layout helps to improve the light distribution of the densely planted canopy, reduce the height difference between plants and the uneven distribution of dry matter (Xue et al., 2015). The plant morphological adaptation caused by dense planting has a "double-edged sword" effect: moderate plant height increase and canopy compactness are conducive to improving the photosynthetic capacity of the group, but excessive leggy growth and reduced branching will weaken individual productivity. Therefore, in dense planting cultivation, the variety characteristics (such as plant compactness and density tolerance) should be combined to regulate the group structure so that the plant morphological adaptation and high yield formation are coordinated.

2.2 Group competition and photosynthetic efficiency regulation mechanism

The main purpose of increasing planting density is to enhance the utilization rate of light energy, space and nutrient resources by the group. Under dense planting conditions, the number of plants per unit area increases, the interception of light by the group is significantly improved, and the utilization of Photosynthetically Active Radiation (PAR) is more sufficient. Studies have shown that the canopy interception rate of high-density soybean populations in the middle growth period can be close to 95%-98%, which is significantly higher than the level of less than 96% under conventional density. Higher interception rate leads to an increase in total photosynthetic production: the dry matter accumulation of the population under dense planting treatment is about 15% higher than that of the control, and the advantage is particularly obvious in the late growth period (R5 of grain filling stage to R7 of maturity stage) (Maitree and Toyota, 2017). However, there is also fierce light competition and interlayer shading within the dense planting population. The upper leaves often obtain too much light and become light saturated, while the lower leaves have reduced photosynthetic efficiency due to long-term low light. This uneven light will increase the growth differences of individuals in the population, which is not conducive to yield stability. By uniform planting (that is, ensuring that the plants are evenly distributed in the field rather than clustered), the coefficient of variation of light interception and assimilation capacity between plants can be significantly reduced, thereby improving the consistency and synergy of the population.

The field experiment of Xu et al. (2021) showed that the coefficient of variation of the grain weight of soybeans planted in uniform strips at high density was 71.5% lower than that of non-uniform distribution, and the group yield was higher and more stable. The shade environment caused by dense planting will also induce a series of physiological responses, such as changes in chlorophyll fluorescence parameters and regulation of hormone levels, to adapt to the low light intensity environment. Studies have shown that under low light conditions, soybean leaves improve light energy utilization efficiency by reducing the light saturation point and maximum photosynthetic rate, while allocating more carbon to stem elongation to break through the upper light limitation. These adaptation strategies alleviate the light energy utilization conflict caused by dense planting to a certain extent, enabling the group to maintain a high net photosynthetic productivity. However, when the density is too high, excessive light competition will cause premature aging of the lower leaves and a decrease in net assimilation, which may eventually offset the benefits of dense planting and increased yield. Therefore, to achieve dense planting and increased yield, it is necessary to take measures (such as breeding dense-tolerant varieties, optimizing row spacing and sowing methods) to reduce excessive competition between plants and maintain coordinated growth of the group while improving the photosynthetic efficiency of the group.

2.3 Dynamic trade-off between pod number and yield per unit area

The impact of dense planting on the yield components of legume crops is complex and critical. Generally speaking, as the planting density increases, the resources available to each plant decrease, resulting in a decrease in the number of pods per plant, the number of grains per pod, and the grain weight; but as the number of plants per unit area increases, the total number of pods and grains in the population may increase, thereby increasing the yield per unit area. This reflects the trade-off between single-plant yield and population yield. A large amount of experimental data supports this point: within a certain density range, crop yield increases with increasing density until it reaches a plateau or peak; after exceeding the optimal density, the yield does not increase but decreases. Taking soybeans as an example, their single-plant yield (mainly determined by the number of pods per plant and grain weight) is extremely sensitive to increased density. Under dense planting treatment, the number of effective branches and full pods per soybean plant decreased significantly, the number of complete pods decreased by more than 20% at low density, and the proportion of unfilled pods increased. At the same time, the thousand-grain weight per plant also tends to decrease. For example, the dry weight of grains per plant under high density is about 28.6% lower than that under normal density (Sichilima et al., 2018). Correspondingly, the yield difference between individual plants increases, and the coefficient of variation of grain yield between different individuals can increase by 6%-30% under high density.

Although the yield per plant decreases, the total yield per unit area often shows an upward trend due to the increase in population density until the balance point between density effect and individual effect is reached. For example, Han et al. (2021) comprehensively evaluated the density tolerance of 90 soybean germplasms under high density stress and found that the grain weight per plant decreased the most under high density, followed by branch-related traits, but the population yield can still remain stable or even increase within a certain range. When the density exceeds the optimal value, the population yield will decrease due to excessive competition, often accompanied by serious lodging and disease problems. Lodging is one of the main limiting factors for high yield of dense planting: densely planted plants have thin and tall stems, weak lodging resistance, and are prone to lodging and breaking under strong winds and rains, resulting in reduced yield. Studies have shown that once soybeans fall over, yield losses can be as high as 20% or more (Di Mauro and Rotundo, 2025). The closed environment caused by dense planting can also easily lead to increased field humidity and the breeding of pathogens. For example, powdery mildew, downy mildew, and sclerotinia are more likely to occur under dense planting conditions. Therefore, in actual production, it is necessary to select appropriate planting density according to specific varieties and ecological conditions to achieve coordinated optimization of single plant and group yields. On the one hand, by improving the branching and pod-bearing ability of dense-tolerant varieties, the negative impact of dense planting on single plant yield can be reduced; on the other hand, through density management, excessive competition and lodging risks can be avoided to ensure the reliable realization of group yield increases.

3 Fertilization Strategy and Nutrient Absorption and Utilization

3.1 Effect of nitrogen, phosphorus and potassium application ratio on root and aboveground growth

Among the various nutrients required for the growth of legume crops, nitrogen (N), phosphorus (P) and potassium (K) are the "three major factors" that determine yield. A reasonable N-P-K supply ratio can coordinate the growth of the underground and aboveground parts of the plant to achieve high and stable yields. The nitrogen supply level has a dual effect on the root development and nitrogen fixation process of legumes: appropriate nitrogen fertilizer is beneficial to the early growth of seedlings and the establishment of the root system, but excessive nitrogen fertilizer will inhibit nodule symbiosis, reduce the number of nodules and nitrogenase activity. Experiments show that without nitrogen application, soybean plants can obtain nitrogen through nitrogen fixation. Although the number of pods per plant is low, the group benefit is high; while the application of excessive chemical nitrogen (such as 60 kg/hectare) significantly reduces the number and quality of nodules, and the dry weight of nodules is reduced by nearly 20% compared with the no nitrogen treatment (Wysokinski et al., 2024). The best strategy is to apply a small amount of nitrogen as a "guide fertilizer" at the time of sowing or in the seedling stage to promote the growth of seedlings, and then rely mainly on biological nitrogen fixation to meet the needs.

Phosphorus is an important element for energy metabolism and root development. Adequate phosphorus supply can stimulate the elongation and branching of bean roots and enhance the nitrogen fixation activity of rhizobia. When phosphorus fertilizer is sufficient, the soybean root system's ability to absorb nitrogen is improved, and the aboveground part of the plant grows vigorously; conversely, phosphorus deficiency will lead to underdeveloped root systems, reduced nitrogen fixation and nitrogen absorption capabilities, short plants, and reduced flowering and pod production. Potassium is closely related to carbohydrate transport and enzyme activity, and has an important impact on bean grain filling and stress resistance. Increasing potassium fertilizer often increases pod fullness and grain weight, and enhances the plant's resistance to lodging and disease. For example, appropriately increasing the proportion of potassium fertilizer under dense planting conditions can compensate for the reduction of nitrogen, maintain the physiological balance of the plant, and thus ensure yield. In the field experiment of Zhou et al. (2019), after reducing the conventional nitrogen fertilizer application by 20% and increasing the potassium fertilizer application by 20%, the root-crown ratio of the soybean population became more reasonable, the root system vitality was enhanced, and the aboveground biomass and yield were the same as or even slightly higher than those of conventional fertilization. This shows that "reducing nitrogen and increasing potassium" is a fertilization adjustment strategy that conforms to the physiological characteristics of legume crops, which helps to give full play to the advantages of legume root nodules in nitrogen fixation and avoid resource waste and negative effects caused by excessive nitrogen fertilizer. In actual production, the N-P-K ratio should be different under different soil fertility conditions: plots with low fertility need to appropriately increase phosphorus and potassium inputs, while plots with high fertility, especially those with rich nitrogen residues in the previous season, should control the amount of nitrogen fertilizer to avoid inhibiting nitrogen fixation. By evaluating nutrient abundance and deficiency through soil testing and formulating a balanced fertilization plan according to local conditions, it can simultaneously promote the formation of a strong root system and a lush canopy of legume crops, and achieve the coordination and unity of underground nitrogen fixation and high-yield growth above ground.

3.2 Regulation of nitrogen fixation activity and absorption efficiency at different topdressing periods

The timing of fertilization has no less impact on nutrient utilization efficiency and crop growth than the amount of fertilizer applied. For legumes, how to timely supplement the nutrients required in the middle and late stages while ensuring nitrogen fixation in the early stage is the key to fertilization strategy. Studies have shown that providing an appropriate amount of nitrogen source in the early growth period helps legume seedlings to establish and grow in the early stage, but if nitrogen is applied too early and too much, it will inhibit nodule formation and reduce the potential for biological nitrogen fixation due to increased inorganic nitrogen levels in the soil (Ciampitti et al., 2021). Therefore, it is generally recommended that nitrogen fertilizer should not be applied excessively at sowing. The nitrogen input in the base fertilizer for legume sowing is usually controlled at around 20-30 kg/ha to promote seedling growth without inhibiting nodules. As the crop grows, nodule nitrogen fixation gradually meets most of the plant's nitrogen needs during the vegetative growth stage. However, after flowering and podding, the demand for nitrogen in legumes increases dramatically, and nodule activity may decrease due to factors such as soil drought and nutrient deficiency. At this time, the appropriate amount of nitrogen fertilizer is beneficial to increase the protein content and yield of grains. The experiment compared the effects of topdressing nitrogen fertilizer at the early flowering stage (R1) and the grain filling stage (R5) of soybeans, and found that nitrogen application at the grain filling stage had a significantly higher yield-promoting effect than nitrogen application at the early flowering stage, while topdressing nitrogen too early at the early flowering stage often had no significant effect on yield.

In a multi-year experiment in the United States, a single nitrogen application at the early flowering stage did not increase soybean yield, while delaying the application of the same amount of nitrogen fertilizer to the grain filling stage had a significant yield-increasing effect. It can be seen that the nitrogen supply "window period" for leguminous crops such as soybeans is in the middle and late reproductive growth. At this time, exogenous nitrogen will not significantly weaken nodule nitrogen fixation (because the plant has accumulated a large amount of nitrogen fixation capacity and nitrogen fixation is weakened in the late growth stage), but can make up for the lack of nitrogen fixation and nitrogen supply. Khalili et al. (2024) suggested that applying 60 kg/ha of nitrogen fertilizer in two times: 1/2 as basal fertilizer and the remaining 1/2 as topdressing at the pod setting stage, combined with the application of an appropriate amount of sulfur fertilizer, can significantly increase soybean seed yield and quality. The topdressing period also has an important impact on nutrient absorption efficiency. Generally speaking, phosphorus and potassium fertilizers should be applied early so that crops can fully utilize them throughout the growth period; while nitrogen fertilizers should be applied in stages or slow/controlled release technology should be used to match the absorption peaks of crops at different stages. In the field experiment in Qiqihar in this study, a small amount of nitrogen topdressing was carried out at the initial flowering stage and the grain filling stage of soybeans. The results showed that the number of pods and the weight of 100 grains treated with topdressing at the grain filling stage were higher than those of the control without topdressing, and the yield increased by about 5%, while the yield increase effect of topdressing at the initial flowering stage was not obvious. This is consistent with the above rule, that is, the response of soybeans to nitrogen is mainly in the late reproductive stage. It should be noted that topdressing too late (such as in the late grain filling stage) is of little significance, because the leaf function declines when approaching maturity, and fertilization is difficult to convert into yield. Fertilization of beans should follow the timing strategy of "light in the front, control in the middle, and supplement in the back": less nitrogen and heavy phosphorus and potassium in the early growth stage, appropriate regulation in the middle stage depending on the growth, and necessary nutrients in the middle and late reproductive stages to maintain a higher functional leaf area and accumulation of assimilated products in the group, thereby achieving high yield.

3.3 Improvement of nutrient utilization efficiency under the synergistic effect of organic-inorganic fertilizers

Long-term practice has proved that the combined application of chemical fertilizers and organic fertilizers (i.e., "organic-inorganic combination") is an important measure to balance crop high yield and soil fertility. This strategy is particularly applicable to legume crops, because organic fertilizers not only provide nutrients, but also improve the physical and chemical properties of the soil, promote the growth of rhizobia, and create a good environment for nitrogen fixation. Li et al. (2024) compared the effects of single chemical fertilizer application and organic-inorganic combination on soybean yield and quality in a long-term positioning experiment in Heilongjiang. The results showed that all fertilization treatments significantly increased yield by 5.1%-18.6% compared with no fertilization, among which the treatment with nitrogen, phosphorus and potassium chemical fertilizers combined with organic fertilizers had the best yield increase effect. The addition of organic fertilizers not only increased yield, but also significantly increased the nutritional content of protein, calcium and iron in soybean grains. Soil analysis shows that organic-inorganic combination can improve soil aggregate structure, increase soil organic matter and quick-acting nutrient content, thereby improving soil fertilizer supply capacity and fertilizer utilization efficiency.

Another soybean field trial conducted in a semi-arid area further demonstrated the significant benefits of organic material application: under the same nutrient input, the soybean yield of chemical fertilizer + organic fertilizer + biofertilizer treatment increased by 28%-79% compared with the treatment of chemical fertilizer alone, and the water use efficiency was also improved simultaneously (Liu et al., 2024). This is attributed to the fact that organic fertilizer improves the soil water and fertilizer retention performance and root growth environment, allowing soybean plants to form a larger and deeper root system (root length and root surface area increased significantly), thereby absorbing water and nutrients more efficiently. Organic fertilizer can also buffer soil pH, provide crop trace elements, activate nutrients such as phosphorus fixed in the soil, and reduce fertilizer nutrient leaching and fixation. For legumes, since nitrogen fixation can partially replace chemical nitrogen fertilizers, using organic fertilizers to provide a basic nitrogen source is particularly in line with their needs. On the one hand, it avoids the inhibition of nodules by applying high amounts of quick-acting nitrogen fertilizers, and on the other hand, the decomposition of organic matter continues to provide nutrients for the crop in the late stage.

The application of organic-inorganic fertilizers achieves a win-win situation of improving soil fertility and increasing crop yields by combining "nurturing the land with nurturing crops". In production, appropriate organic fertilizer sources (such as farmyard manure, green manure, crop straw compost, etc.) should be selected according to specific conditions for application, and the replacement ratio should be reasonably determined. For example, 20%-30% of the nutrients can generally be provided by organic fertilizers, and the rest can be supplemented by chemical fertilizers, thereby reducing the use of chemical fertilizers and optimizing the input structure. It should be noted that organic fertilizers have low nutrient content and are released slowly. When applying, they should be decomposed in advance and applied early to coincide with the peak of crop fertilizer absorption. By scientifically implementing the organic-inorganic combined fertilization strategy, the nutrient utilization efficiency and yield level of legume crops can be effectively improved, and a virtuous cycle of the agricultural environment can be promoted.

4 Analysis of the Interactive Effect of Dense Planting and Fertilization

4.1 Identification of the optimal combination: medium density + balanced fertilization mode

In actual production, the degree of dense planting and the level of fertilization need to be coordinated and matched to achieve the best yield increase effect. Too low density will lead to waste of resources, and even if more fertilizer is applied, it will be difficult to fully play its role; on the contrary, if high-density planting is insufficient in nutrient supply, the growth of crops will be inhibited due to fierce competition, and it will be difficult to produce high yields. Therefore, different regions and different seasons should screen out the optimal combination of planting density and fertilization amount according to specific varieties and ecological conditions. In recent years, many studies have determined the optimal density-fertilization scheme for crops such as soybeans through two-factor field experiments or model simulations. For example, Hao et al. (2023) used a quadratic regression design in Northeast China, and simultaneously examined the planting density (300,000-600,000 plants/ha) and NPK fertilization level to optimize the yield response surface. The results showed that the theoretical optimal combination was: density 45.37×104 plants/ha, nitrogen application 98.4 kg, phosphorus application 218.96 kg, potassium application 47.62 kg, and the expected yield could reach 3816.7 kg/ha. This result quantitatively provides a reference model for high soybean yield in the local area. Of course, the optimal values in different regions vary and need to be adjusted according to soil fertility and variety characteristics. But overall, "medium to high density + balanced and sufficient nutrients" is one of the common characteristic patterns of high bean yield.

Through interaction analysis, it can be found that reasonable fertilization can expand the response range of crops to planting density. For example, under low fertility conditions, soybean yield reaches a plateau earlier with increasing density, while under sufficient fertilization conditions, the yield plateau is delayed, and crops can continue to benefit from higher density. This shows that fertilization management can improve the density tolerance of crops. Conversely, close planting measures can also increase the marginal return of fertilizers. Within a certain range, high-density groups have higher utilization efficiency for each unit of fertilizer nutrients. Therefore, the optimization of the two should be carried out in a coordinated manner. For example, for densely planted varieties with the potential for dense planting, the fertilizer input can be increased accordingly to give full play to its yield potential; while for creeping or large-sized varieties that require thin planting, the amount of fertilizer should be properly controlled to avoid closure and leggy growth.

4.2 Synergistic improvement of biomass accumulation and resource allocation

The goal of dense planting and fertilization optimization is to simultaneously promote the overall biomass accumulation of crops and the allocation to economic output, and improve the harvest index. Under suitable density and sufficient nutrient conditions, legume crops can maintain a higher group photosynthetic productivity and a longer functional period, so that vegetative growth and reproductive growth can be coordinated. The study found that the plasticity of individual plants enables them to adjust resource allocation strategies under different planting densities and nutrient levels: in sparse planting and low nutrient conditions, plants tend to increase root input (increase root-crown ratio) to obtain more resources; in dense planting and nutrient-sufficient environments, plants allocate more dry matter to the aboveground parts, especially pods and grains, to improve competitiveness and reproductive success rate. Therefore, the combined optimization treatment often presents the characteristics of both strong roots and aboveground parts and sufficient reproductive allocation. The study by Szpunar-Krok et al. (2023) showed that in the treatment of 30 kg nitrogen application and rhizobium inoculation, the number of pods and grains per soybean plant increased significantly, and the number of nodules and dry weight were also higher than those in the treatment without nitrogen application, achieving the simultaneous enhancement of underground nitrogen fixation capacity and aboveground pod-forming capacity. This proves that reasonable nutrient supply can promote plants to accumulate more assimilated products and effectively allocate them to grains. In the experiment, the total dry matter mass of soybean populations treated with the best combination increased by 14% compared with the control, of which the proportion allocated to grains also increased by about 5 percentage points, and the harvest index was significantly improved.

It is particularly worth mentioning that the optimization of dense planting and fertilization can also improve the uniformity between individuals in the group, reduce the occurrence of "small old seedlings" or "empty stalks", and enable almost all plants to produce pods and seeds. This means that the unstable loss of group biomass and yield is reduced, and the overall yield increase effect is more stable (Xu et al., 2021). The optimized combination can delay the aging process of plants by improving the nutritional status and group structure of plants. For example, the group closure formed by appropriate topdressing of nitrogen fertilizer and dense planting can often maintain a longer green leaf functional period (extend leaf aging, the so-called "greed for green"), continue photosynthesis in the late growth period and transport nutrients to the grains. Of course, excessive "greed for green" may lead to delayed maturity, but it can generally be regulated through variety selection and chemical control measures. In practical applications, the biological basis of the synergy between dense planting and fertilization is reflected in: increasing the photosynthetic area and efficiency of the entire group (dense planting effect), while ensuring the efficient conversion and distribution of each unit of photosynthetic products (fertilization effect). The former provides the "source" and the latter strengthens the "sink", and the two are connected through "flow" (transport and distribution of nutrients and assimilated products). If the management is proper, the three aspects of source, flow and sink are all enhanced, and a significant yield increase effect will be achieved. On the contrary, if the two aspects do not match (such as too high density and insufficient source or insufficient fertility and limited sink), the yield increase potential cannot be fully realized. Therefore, strengthening the monitoring and regulation of the relationship between crop source, flow and sink, so that dense planting and fertilization effects complement each other, is the key to achieving a coordinated increase in crop yields.

4.3 Analysis of crop adaptation response and plasticity to resource pressure

As an annual crop, legume crops have a certain phenotypic plasticity to cope with density and nutrient changes. This study observed that soybean plants can adapt to resource pressure by changing morphological and physiological characteristics under different treatments. For example, under high density or low fertilizer conditions, plants give priority to top growth, which is manifested as longer stems and accelerated inflorescence differentiation, in order to seize space and reproduce successfully; while under low density or high fertilizer conditions, plants tend to increase the number of branches and leaves to make full use of resources and the environment (Cassel et al., 2025). This plastic response enables crops to buffer the stress caused by management measures within a certain range, thereby maintaining basic growth and yield. However, the degree of plasticity varies among different varieties, which determines their adaptability to dense planting and fertilization. Dense-tolerant varieties usually have weaker marginal branching habits and more upright plant types, with less yield loss under high density; while varieties that perform well in fertile soils often have a significant decrease in yield under poor conditions. Therefore, when promoting dense planting and fertilization optimization technology, corresponding cultivation strategies should be selected in combination with variety characteristics.

On the other hand, crops can also be induced to produce favorable adaptive responses through reasonable management. For example, dense planting and nitrogen fertilizer regulation can moderately delay plant aging, increase chlorophyll content, form a "continuous reservoir" effect, and use more late photosynthetic products for grain filling. In the Qiqihar experiment, we noticed that in the treatment of controlled-release nitrogen fertilizer, the leaf function of soybean population was better in the later stage, and the SPAD value of leaves in the grain filling stage was 2-3 units higher than that of ordinary urea treatment, indicating that the plant's nutrient supply was more sustained, thereby improving the fullness of pods and grains. For example, in the high-density nitrogen reduction and potassium increase treatment in Zhumadian, although the number of branches of the plant decreased, the number of pods on the main stem increased significantly, and the proportion of the total number of pods increased from 60% of the control to 75%, reflecting the compensatory mechanism of the plant to concentrate resources on the main stem to be strong. It can be seen that crops themselves have a certain regulatory ability, and we should use this ability to guide the shaping of plants in a direction conducive to high yield through fine management.

The interactive management of dense planting and fertilization needs to respect the biological characteristics and adaptation strategies of crops. On the one hand, it is necessary to prevent management measures from exceeding the range that crop plasticity can adjust (such as irreversible yield loss caused by excessive density); on the other hand, management can stimulate crop potential (such as stimulating marginal branching and pod formation, extending the functional period, etc.). For different ecological regions and varieties, we should deepen the research on the physiological mechanisms of crop dense planting tolerance and nutrient efficiency to provide a basis for adjusting cultivation measures. For example, through field phenotypic observation combined with molecular marker analysis, we can screen out genotypes related to dense planting tolerance and fertilizer tolerance to guide breeding and cultivation. This will help to further improve the adaptability of legume crops to resources and the environment, and achieve the maximum yield benefit of dense planting and fertilization optimization.

5 Case Study: Regional Dense Planting and Fertilization to Increase Yield

This study selected two typical bean planting areas in the north and south of my country, Zhumadian, Henan and Qiqihar, Heilongjiang, to analyze the application effects of dense planting and fertilization technology in different regions and different rows of crops. These two regions represent the main peanut producing areas and soybean producing areas, respectively, with very different ecological conditions and typicality.

5.1 Demonstration of high-yield dense planting and fertilization of peanuts in Zhumadian, Henan

Zhumadian is located in the southern part of the Huanghuai Plain and is an important peanut production base in China, with annual planting area and total output ranking among the top. However, the long-term continuous planting of peanuts in the local area has led to a decline in soil fertility and aggravated pests and diseases, limiting the increase in yield. In order to solve this dilemma, in recent years, local agricultural departments and scientific research institutions have cooperated to carry out high-yield demonstrations of dense planting and matching fertilization for peanuts. The demonstration field adopts a planting density that is about 20% higher than the traditional density (about 180,000 plants/hectare), and applies soil testing and formula fertilization technology: on the basis of applying sufficient organic fertilizer as base fertilizer, nitrogen, phosphorus and potassium are applied in a balanced manner (the ratio of the three elements is about 1:0.8:1.2), and trace element fertilizers such as calcium, boron and molybdenum are added to prevent deficiency. In terms of fertilization methods, mechanical deep fertilization and layered strip fertilization are promoted, that is, slow/controlled release fertilizers are applied to the root concentration layer. A series of technical integrations have significantly improved the growth environment of peanuts. The demonstration results show that the individual robustness of peanuts in the densely planted and fertilized fields is not significantly lower than that of conventional ones, while the number of pods in the group has increased significantly, and the average yield per mu has increased by about 15% to 20% (Figure 1) (Wang et al., 2022). Among them, the treatment with special slow-release fertilizers and layered application has the best yield increase effect, with an average increase of 19.0% to 27.3% over the conventional yield of farmers in two years. At the same time, the roots of the plants penetrate deeper during the pod-setting period, and the dry weight and length of the roots in the 0 cm-20 cm soil layer are significantly higher than those of the control, showing a strong absorption capacity. In terms of disease occurrence, due to reasonable dense planting and sufficient nutrients, the overall stress resistance of the plants is improved, and the incidence of leaf spot and root rot is about 5 percentage points lower than that of the control. Economic benefit analysis shows that the dense planting and fertilization demonstration field increased income by about 100 yuan per mu, and the income increased without significantly increasing the input cost (part of the slow-release fertilizer replaced the conventional fertilizer dosage). The Zhumadian case proves that the implementation of dense planting + optimized fertilization in the main peanut producing areas can effectively break through the traditional yield bottleneck and achieve stable and high yields, which is very attractive to farmers. At present, this technology is also being gradually promoted in other counties and cities in Henan Province, and is welcomed by large-scale growers.

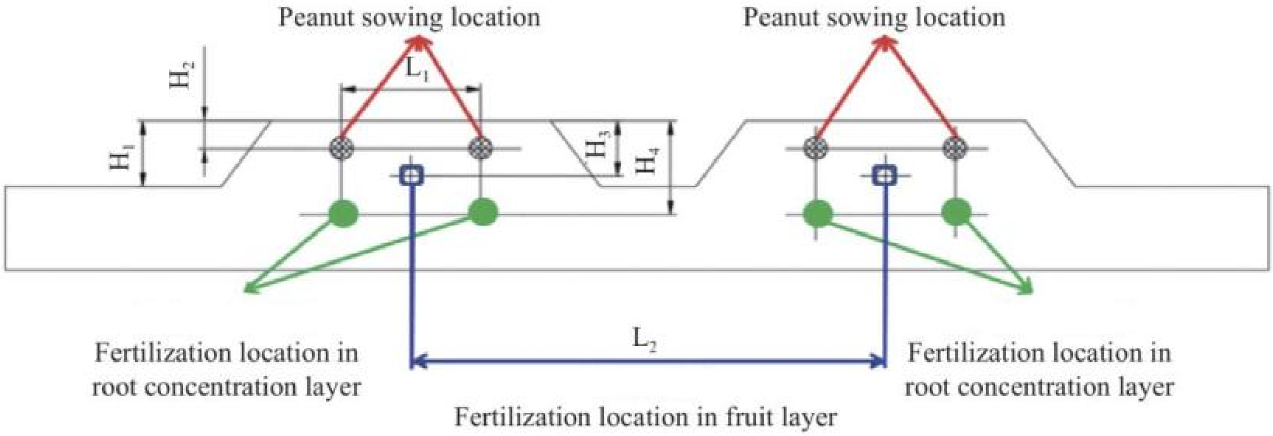

Figure 1 Illustration of peanut sowing and fertilization location (Adopted from Wang et al., 2022)

Image caption: L1—Row distance 25 cm; L2—Rridge distance 85 cm; H1—Ridge height 15 cm; H2—Sowing depth 4 cm; H3—Fertilization depth at fruiting layer 8 cm; H4—Fertilization depth at root concentrated layer 16 cm (Adopted from Wang et al., 2022)

5.2 Example of soybean dense planting and fertilization yield increase in Qiqihar, Heilongjiang

Qiqihar is located in the cold black soil area of Northeast my country and is a traditional soybean planting area and soybean breeding base in China. The local climate is cold and the frost-free period is short, and most soybean varieties are early-maturing or medium-early maturing types. In the past, the soybean planting density in Qiqihar was relatively low, about 200,000 plants per hectare, and the yield was around 1.8 tons per hectare. In recent years, with the implementation of the soybean revitalization plan, researchers have tried to increase the yield of soybeans in the north by increasing density and improving fertilization. In the dense planting and matching cultivation experiment of new and superior high-protein soybean varieties carried out by the Heilongjiang Academy of Agricultural Sciences in Qiqihar, the yield performance under different sowing periods and planting density combinations was compared. The results show that early sowing at the right time (early May) can make full use of the growth period and make the yield higher than the conventional sowing period; at the same time, under early sowing conditions, the density increased significantly from 250,000 to 350,000 plants per hectare, and the yield increase decreased when it continued to increase to 450,000. Comprehensive analysis shows that the optimal cultivation plan for local early-maturing varieties is to sow before May 5, with a density of about 300,000 plants per hectare. Based on this plan, large-scale demonstrations were carried out, and the average soybean yield per mu in multiple test sites in Qiqihar reached 300 kg, which is more than 10% higher than the conventional yield of farmers. In terms of fertilization management, a strategy of nitrogen-based, phosphorus-stabilizing and potassium-increasing was adopted according to the nutrient characteristics of black soil: 40 kg of pure nitrogen, 60 kg of phosphorus fertilizer, and 45 kg of potassium fertilizer were applied per hectare, and molybdenum fertilizer was applied in combination with the molybdenum requirement of soybeans. No nitrogen fertilizer was applied in the later stage to prevent vigorous growth and lodging (Hao et al., 2023). Under this fertilization measure, the nutritional growth and reproductive growth of densely planted soybean groups were coordinated, the number of effective pods per plant decreased slightly, but the total number of pods in the group increased significantly; more importantly, the protein and fat content of the grains increased simultaneously, and there was no high yield accompanied by a decrease in quality. Field surveys showed that the pods of the group under high density were more evenly distributed, and there were more effective pods in the lower part, which increased the harvest index. The experiment also paid special attention to economic benefits: due to the increase in soybean seed and fertilizer input, the cost increased slightly, but due to the increase in yield and the support of the national soybean subsidy policy, the net income still increased. Farmers reported that as long as the yield per unit area increased by more than 0.1 tons/hectare, the cost of dense planting and increased fertilization could be offset, and the yield increase in the demonstration generally exceeded 0.2 tons/hectare, with significant income increase benefits. Qiqihar's practical experience has proved that in high-latitude black soil areas, through dense planting of suitable varieties and precise fertilization, it is entirely possible to break through the traditional soybean yield limit and achieve a double increase in yield and quality. This has set a typical example for the large-scale promotion of high-yield and high-quality soybean cultivation in Northeast China.

5.3 Comparison of application results and farmer feedback

By comparing the high-yield dense planting and fertilization demonstration results in two typical areas, Zhumadian, Henan and Qiqihar, Heilongjiang, it can be seen that although there are obvious differences in crop types and ecological conditions, "dense planting + optimized fertilization" as a yield-increasing cultivation strategy has shown good adaptability and promotion potential in the main peanut and soybean producing areas in the north and south. The peanut demonstration area in Zhumadian has achieved a 15% to 20% increase in yield per mu by reasonable density increase and combined with soil testing and formula fertilization and slow-release fertilizer deep application technology. The yield increase of the best treatment reached nearly 27.3%, and the root rooting depth and disease resistance were significantly improved. On the basis of optimizing the sowing period and density, Qiqihar soybeans achieved an average yield of more than 300 kilograms per mu through targeted fertilization (stabilizing phosphorus, increasing potassium, and applying molybdenum), which was more than 10% higher than the conventional yield. At the same time, the protein and fat content of the grains were both improved, and the quality did not decrease but increased.

From the perspective of the occurrence of diseases and insect pests, the demonstration fields in both places showed that reasonable dense planting and supporting fertilization had a positive effect on enhancing the group's stress resistance. The incidence of leaf spot and root rot in the peanut fields in Zhumadian was about 5 percentage points lower than that in the control. There was no concentrated outbreak of diseases caused by high density in the soybean fields in Qiqihar, indicating that high-density management will not cause ecological imbalance in the group under the premise of ensuring nutrient supply. Enhanced root vitality and improved pod distribution are also advantageous features reflected in the demonstrations in both places.

In terms of farmer feedback, the two trials were welcomed by growers. Farmers in Zhumadian generally recognized the "high yield and stable income" effect brought by dense planting and fertilization, and because some slow-release fertilizers replaced conventional fertilizers, the input cost did not increase significantly, and the average income per mu increased by more than 100 yuan; the Qiqihar demonstration further verified that under the support of the national soybean subsidy policy, the benefits brought by high-density cultivation were significantly better than the cost increase. Farmers generally said that as long as the yield increased by more than 0.1 tons/hectare, the input could be covered, and the demonstration area generally exceeded 0.2 tons/hectare, with good economic returns.

The practical results of the two places show that the integrated application of dense planting and precision fertilization technology has become an important path to break through the current bottleneck of crop yields. Improving the group yield level on the basis of ensuring the growth quality of individual plants, taking into account both ecological and economic benefits, has important reference value for promoting the high-yield and high-quality development of grain and cash crops in different ecological zones in the north and south.

6 Agronomic and Economic Benefit Evaluation

6.1 Cost input and fertilizer utilization efficiency analysis

When evaluating the dense planting and fertilization optimization strategy, we should not only look at the yield benefit, but also consider the changes in cost input and resource utilization efficiency. Dense planting often means that more seeds and possible pest control costs need to be invested, but its yield increase benefits can usually make up for these investments. If dense planting has a significant yield increase benefit, the seed cost and management cost per unit output will decrease, which will increase the marginal benefit. From the case study of this study, the seed usage of Zhumadian high-density treatment increased by about 15%, which is equivalent to an increase in cost of about 150 yuan/hectare, but the output value increased by more than 1,000 yuan/hectare, and the cost-benefit ratio was significantly improved. On the other hand, the impact of optimized fertilization strategy on cost and efficiency is more direct: nitrogen reduction measures can reduce the input of expensive nitrogen fertilizers, and although the increase in potassium fertilizers increases costs, the utilization rate of potassium fertilizers is usually improved and the residual effect can last for many years.

From a national perspective, China's fertilizer utilization rate is low at only 30%-40%, and nearly half of the fertilizer nutrients are lost and wasted. By balancing fertilization and improving fertilizer varieties (such as controlled-release fertilizers and biofertilizers), fertilizer utilization efficiency is expected to increase to more than 50%, thereby reducing the amount of fertilizer used at the same yield or increasing yield at the same amount (Zhou et al., 2019; Pierozan et al., 2023). Economically, this means a reduction in the cost of fertilizer per kilogram of grain. Taking controlled-release fertilizers as an example, although their price is higher than that of ordinary fertilizers, because of the reduction of loss and multiple applications, crops actually get more nutrients, the fertilizer effect period is extended, and the unit nutrient output rate is improved. For example, in the Qiqihar experiment, the nitrogen input of the controlled-release fertilizer treatment was the same as that of the conventional treatment, but the nitrogen fertilizer recovery rate (the proportion of nitrogen absorbed by the plant to the amount of nitrogen applied) increased by about 10 percentage points, which is equivalent to producing more products without increasing input. Agricultural producers usually value the input-output ratio, and through optimized management, "one input, multiple outputs" can be achieved. Density planting and fertilization optimization may also bring some hidden benefits. For example, nitrogen reduction can reduce energy consumption and carbon emissions caused by nitrogen fertilizer production and application, which is beneficial to long-term environmental and economic benefits.

Of course, in specific applications, attention should be paid to the marginal balance between input and benefit. For example, blindly too high density may lead to increased diseases and reduced quality, thereby offsetting economic benefits. Therefore, it should be stopped when the output and benefit peaks are reached. Similarly, the more fertilizer input, the better. It should be based on achieving efficient utilization. Increasing input blindly will only reduce input-output efficiency. By measuring the cost-effectiveness of different technical combinations, farmers can be provided with a basis for decision-making: such as whether it is cost-effective to use more expensive new fertilizers, and whether the additional management brought by increased density is worthwhile. Optimized management improves resource utilization and output efficiency, and has significant economic rationality. Especially in the context of rising fertilizer prices and stricter environmental regulations, measures to reduce fertilizer and increase efficiency can reduce planting costs, increase profits and reduce environmental costs, which can be described as a win-win move.

6.2 The impact of dense planting on the incidence of diseases and prevention and control suggestions

Dense planting is a "double-edged sword". While increasing production, it may also change the field microclimate, thereby affecting the occurrence and development of pests and diseases. Generally, dense planting will lead to a reduction in plant spacing, poor ventilation and light transmission, and field humidity and temperature that are more suitable for the spread of certain diseases such as fungal diseases. For example, soybean powdery mildew and sclerotinia are more likely to break out in a closed and humid environment, and the occurrence of white mold (sclerotinia) often increases with the increase in planting density. However, not all diseases increase under dense planting conditions. Some root diseases caused by soil-borne pathogens may be reduced due to shading and cooling of the soil by dense planting. The key is that dense planting changes the environmental factors and host resistance in the disease triangle (host-pathogen-environment).

In order to minimize the disease losses that may be caused by dense planting, the following prevention and control strategies can be adopted: select disease-resistant and dense-tolerant varieties to reduce the possibility of disease occurrence from the variety. For example, densely planted varieties tend to have upright plant shapes, narrow leaves, good ventilation at the bottom, and stronger resistance to gray spot diseases. Optimize the cultivation layout, such as reasonable row spacing and strip planting, so that the field can reach the target density while retaining certain ventilation channels (Potratz et al., 2019). Implement enhanced disease monitoring and prevention in densely planted fields. For example, pay close attention to the source of sclerotinia disease before and after the flowering period of soybeans, and spray protective fungicides in advance if necessary (Yang et al., 2022). Spraying carbendazim at the beginning of flowering to prevent sclerotinia disease has good results, and no large-scale disease outbreaks have occurred during the entire growth period. Plants treated with sufficient potassium fertilizers also show higher resistance to infection by pathogens due to tissue reinforcement, which suggests that balanced fertilization can improve crop health to a certain extent. It is worth noting that dense planting may also affect pest dynamics. Closed plants and more abundant green volume may attract leaf-feeding pests and provide a better shelter environment for natural enemies of pests. Taking Zhumadian as an example, the occurrence of aphids in high-density fields was slightly later than that in the control and the density was lower, which may be related to the increased activities of natural enemies such as ladybugs in the closed environment. However, in extreme years, the high humidity caused by dense planting may also be conducive to the reproduction of aphids, etc., and chemical or biological control needs to be strengthened depending on the situation.

When promoting dense planting technology, plant protection measures should be improved to include the risks of pests and diseases that may be aggravated by dense planting into the management scope. On the one hand, the occurrence of pests and diseases can be reduced through cultivation of disease resistance and ecological control; on the other hand, once there are signs of pests and diseases, appropriate pesticides should be used in time to prevent further spread. Fortunately, modern agriculture has a wealth of plant protection technologies, such as drone spraying and intelligent monitoring, which can help achieve efficient pest and disease management of high-density crops. In short, dense planting does not necessarily mean a disaster of pests and diseases. As long as targeted prevention and control measures are taken in advance, it is entirely possible to increase density without increasing harm and achieve the net benefit of dense planting and increased production.

6.3 Technology extension evaluation

Whether an agricultural yield-increasing technology can be widely promoted depends not only on its economic benefits, but also on farmers' acceptance and regional adaptability. In general, farmers are most receptive to technologies that are low-cost, easy to implement and have obvious effects. The close planting technology itself is relatively simple. It can be implemented by adjusting the sowing amount and planting method. The cost increase is small and the effect is seen in the season, so farmers are willing to try it. In Henan, Heilongjiang and other places, most growers are willing to increase the density appropriately under the guidance of experts to observe the changes in yield. Experienced farmers also realize that the optimal density varies under different years. They hope to obtain more precise guidance (for example, through the annual planting recommendations issued by rural extension departments), which provides space for the intervention of precision agricultural technology. In fertilization optimization technology, "input reduction" measures such as reducing nitrogen and increasing potassium are easy to accept because farmers directly feel the benefits of cost reduction. However, the adoption of new fertilizers (such as controlled-release fertilizers and bio-organic fertilizers) is relatively cautious, and the main concerns are price and effect stability. After the trial demonstration in Qiqihar, some cooperatives and large households expressed their willingness to try controlled-release fertilizers, but hoped to be able to subsidize part of the cost through government projects and obtain technical support during the trial period. This shows that the promotion of new fertilizers requires supporting policies and services. In addition, different regions have different adaptability to these technologies. Close planting is more effective in areas with high soil fertility and good irrigation conditions. If blindly close planting is carried out in arid and barren areas, the risk is greater. When promoting, the regional resource endowment must be fully considered. For example, the black soil area in Northeast China has abundant rainfall, and high yields can be achieved through supporting plant protection, while the arid area in Northwest China is more suitable for combining with water-saving irrigation technology (such as the drip irrigation and close planting model in Xinjiang). In terms of fertilization strategy, the acidic soil in the south and the black calcium soil in the north respond differently to nutrients, and different formulas and proportions should also be recommended in a targeted manner (Yoshihira et al., 2020; Hao et al., 2023).

Strengthen the construction of demonstration areas and on-site observations to allow farmers to intuitively understand the effects of the technology. Just as the demonstration fields in Zhumadian and Qiqihar have played a radiating role, successful cases are the most convincing promotion materials. Through training and concise manuals, farmers are taught the key points of operation, such as how to adjust the seed drill to achieve reasonable close planting, how to identify the field symptoms of insufficient or excessive fertilizer, etc. The promotion department can provide farmers with customized fertilization recommendations in combination with soil testing and formula fertilization projects to lower the threshold for them to explore on their own. Green yield-increasing technologies are encouraged at the policy level, and farmers who adopt measures to reduce weight and increase efficiency are given appropriate subsidies or rewards to enhance their enthusiasm. For example, the soybean and corn strip composite planting promoted by the state in recent years combines the advantages of close planting and legume nitrogen fixation, and certain material support is given to demonstration farmers during the promotion process. The close planting and fertilization optimization technology itself has a good scientific basis and practical effect. As long as it is guided by reasonable promotion strategies and policies, farmers are willing to accept and apply these technologies.

7 Conclusion

This study focused on the dense planting and fertilization strategies in high-yield cultivation of legume crops, and the following main insights were obtained in combination with literature and field experiments. Moderate dense planting can increase the yield per unit area by changing plant morphology (increasing plant height and reducing branching) and improving the photosynthetic efficiency of the group, but excessive dense planting will lead to a decrease in single plant yield and an increase in the risk of lodging and disease. There is an optimal range of density that needs to be carefully considered. Scientific fertilization (especially balanced N-P-K supply) is crucial for legume crops to fully realize their nitrogen fixation potential and achieve high and stable yields. Excessive nitrogen fertilizer inhibits nitrogen fixation without significant yield increase benefits, and the amount and application period of nitrogen fertilizer should be optimized; sufficient phosphorus and potassium nutrition can promote root development and grain plumpness, and improve nutrient utilization. There is a significant interactive effect between dense planting and fertilization: reasonable fertilization can expand the adaptability of crops to dense planting, and appropriate density can increase the marginal return of fertilizer. The coordinated optimization of the two can achieve a superimposed gain in yield. Field demonstrations show that the modes of "high density + nitrogen reduction and potassium increase" and "medium density + controlled-release fertilizer" have achieved yield increase or cost saving effects in different regions, verifying the feasibility of theoretical analysis. These findings show that in the cultivation of legumes, increasing density without increasing fertilizer or increasing fertilizer without increasing density is insufficient, and only by taking both into account can the potential for increasing yield be maximized. The practical revelation of this study is that the optimization of agronomic measures should start from the overall growth and development of crops, pay attention to the interaction between factors, and achieve high yield and high efficiency through comprehensive management. For example, when promoting soybean high-yield technology, farmers should not only be told to "plant densely" but also be told how to "keep up with fertilizer"; vice versa, when promoting formula fertilization, appropriate group regulation technology should also be used.

Through this study, it can be clearly understood that optimizing dense planting and fertilization are not two independent ways to increase production, but an organically integrated whole with the unique value of synergistic efficiency. From the perspective of the crops themselves, dense planting focuses on improving light energy utilization and the upper limit of group yield, while fertilization optimization focuses on meeting nutritional needs and improving conversion efficiency. The combination of the two can simultaneously grasp the "source" and "flow" of yield formation and turn the potential increase in yield into actual yield. Specifically, under the condition of relatively sufficient resources, dense planting provides more plants with growth space, and sufficient and balanced nutrient supply ensures that each plant has enough "food" to grow robustly and bear fruit, so that the group yield is significantly higher than conventional management. Our experimental results show that the yield increase brought by comprehensive measures is often higher than the simple addition of the effects of single measures. For example, dense planting or potassium increase in the demonstration field in Zhumadian only increased yield by about 5%, while the combination of the two achieved an increase of more than 13%. This "1+1>2" synergistic effect is the value of optimizing dense planting and fertilization strategies. Equally important, collaborative management can also help improve resource utilization efficiency and sustainability. High yields are often accompanied by high resource inputs, but under the dense planting + optimized fertilization model, the amount of water, fertilizer, land and other resources consumed per unit yield is reduced, reflecting a higher input-output ratio and environmental friendliness. For example, by reducing the use of excessive nitrogen fertilizer and increasing nitrogen fixation in legumes, not only the yield is maintained, but also the loss of nitrogen fertilizer and greenhouse gas emissions are reduced. It can be said that this synergistic optimization achieves the unity of yield, efficiency and environmental benefits. In addition, this strategy also provides a reference for other crops. Although this study focuses on legumes, the principle of synergistic increase in yield by dense planting and fertilization is also applicable to cereals, potatoes, etc., and can be extended to the concept of integrated cultivation management. The synergistic value of optimizing dense planting and fertilization strategies is reflected in the fact that the increase in yield and efficiency far exceeds that of a single technology, which is of great significance for improving the quality and efficiency of modern agriculture and saving costs and reducing pollution. In the future promotion of agricultural science and technology, this integrated management approach should be vigorously advocated to achieve higher-level goals of increasing grain production and sustainable agricultural development.

Looking to the future, with the in-depth understanding of crop growth mechanisms and agricultural information technology, dense planting and fertilization optimization will move towards a more precise and intelligent direction. At the regional scale, differentiated legume cultivation patterns can be formulated based on the climate, soil and production conditions of different ecological zones. For example, "dense planting + water-fertilizer integration" is promoted in water-rich areas, "low density + fertilizer conservation and fertilization" is promoted in dry and thin land, and "reasonable dense planting + drone variable fertilization" is explored in plain areas with high mechanization levels. Through big data and model simulation, the optimal density and fertilization schemes in different regions and years can be predicted to guide farmers to make decisions in advance. In field management, the development of precision sowing and intelligent fertilization equipment makes it possible to achieve precise dense planting and precise fertilization. Variable seeders can divide and differentiate fields according to soil fertility or historical yields to ensure that more seedlings are left in fertile land and fewer seedlings are left in barren land, so as to achieve density space optimization. Similarly, technologies such as soil nutrient remote sensing and plant nutrition diagnosis can instantly guide the adjustment of fertilizer amount and ratio to avoid general "one-size-fits-all" fertilization. With the help of IoT monitoring and artificial intelligence decision-making systems, farmers can "drive" farmland like driving a car, dynamically adjusting density and nutrients to adapt to weather changes and crop growth. These technological advances will greatly improve the level of refinement of dense planting and fertilization management, and further release the potential for increased production of legumes.

At the same time, under the guidance of the "carbon peak and carbon neutrality" strategy and green agricultural policies, the dense planting and fertilization mode that reduces fertilizer and increases efficiency and improves the utilization of legume nitrogen fixation has broad development prospects. Legume crops such as soybeans are considered to be one of the important means to reduce the use of chemical fertilizers and reduce carbon footprint in the agricultural field because of their nitrogen fixation. Promoting dense planting of legumes to improve land productivity and supplemented by scientific fertilization to reduce dependence on chemical fertilizers is in line with the requirements of green development. It can be foreseen that in the future, the country will pay more attention to the research and development and promotion of such technologies in the revitalization of soybeans and the protection of cultivated land. With the establishment of a regionalized precision management system and the improvement of farmers' scientific literacy, optimizing dense planting and fertilization strategies will bring steady increases in production for legumes on a larger scale, and achieve quality improvement, efficiency enhancement and sustainable development of my country's legume production. While ensuring food security, this path will also contribute China's experience to the global response to agricultural resource and environmental challenges, and help build a new agricultural pattern of high yield, high efficiency, resource conservation and environmental friendliness.

Acknowledgments
We are grateful to Dr. T. Zhang for this assistance with the serious reading and helpful discussions during the course of this work.

Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References
Cassel J.L., Rother G.M., Maldaner B.A., Pimenta B.D., Ludwig R.L., and dos Santos D.B., 2025, Morphological changes in soybean cultivars subjected to apical dominance removal at phenological stages, Ciência Rural, 55(1): e20230375.
https://doi.org/10.1590/0103-8478cr20230375

Ciampitti I., de Borja Reis A.F., Córdova S.C., Castellano M., Archontoulis S., Correndo A., De Almeida L.F.A., and Moro Rosso L.M., 2021, Revisiting biological nitrogen fixation dynamics in soybeans, Frontiers in Plant Science, 12: 727021.
https://doi.org/10.3389/fpls.2021.727021

Di Mauro G., and Rotundo J., 2025, Lodging dynamics and seed yield for two soybean genotypes with contrasting lodging-susceptibility, European Journal of Agronomy, 163: 127445.
https://doi.org/10.1016/j.eja.2024.127445

Fan Y.F., Yang F., Liu Q.L., Chen J.X., Wang R., Luo S.L., and Yang W.Y., 2017, Effects of shading on leaf structure and photosynthetic fluorescence characteristics of soybean seedlings in maize-soybean relay intercropping system, Acta Agronomica Sinica, 43(2): 277-285.
https://doi.org/10.3724/SP.J.1006.2017.00277

Han D.Z., Wang S., Jia H.C., Zhang L., Lu W.C., Li Y.H., and Qiu L.J., 2021, Comprehensive evaluation and screening of high density resistant soybean germplasm based on tightness tolerance index and principal component analysis, Soybean Science, 40(4): 445-456.

Hao H., Lv S., and Wang F., 2023, Optimal planting density and nutrient application of soybeans: a case study in Northeastern China, Agronomy, 13(12): 2902.
https://doi.org/10.3390/agronomy13122902

Khalili A., Khalofah A., Ramesh A., and Sharma M.P., 2024, Temporal synchronization of nitrogen and sulfur fertilization: impacts on nutrient uptake, use efficiency, productivity, and relationships with other micronutrients in soybean, Agronomy, 14(3): 570.
https://doi.org/10.3390/agronomy14030570

Li M.Q., Zou W.X., Han X.Z., Yan J., Chen X., and Lu X.C., 2024, Long-term balanced NPK fertilization increases soybean yield, grain nutrient and isoflavone contents and improves fertility of soybean fields, Journal of Plant Nutrition and Fertilizers, 30(11): 2221-2229.
https://doi.org/10.11674/zwyf.2024140

Liu Y., Liu C., Wei L., Zhang X., Liu Q., Bai J., Wang X., and Zhang S., 2024, Additional organic and bacterium fertilizer input regulated soybean root architecture and dry matter distribution for a sustainable yield in the semi-arid region of China, PLOS ONE, 19(7): e0305836.
https://doi.org/10.1371/journal.pone.0305836

Maitree L., and Toyota M., 2017, A high seed yield and associated attributes of dry matter production achieved by recent Japanese soybean cultivars, Plant Production Science, 20(2): 193-204.
https://doi.org/10.1080/1343943x.2017.1294463

Pierozan Junior C., Favarin J.L., Baptistella J.L.C., de Almeida R.E.M., Oliveira S.M., Lago B.C., and Tezotto T., 2023, Controlled release urea increases soybean yield without compromising symbiotic nitrogen fixation, Experimental Agriculture, 59: e1.
https://doi.org/10.1017/S0014479722000540

Potratz D.J., Mourtzinis S., Gaska J., Lauer J., Arriaga F., and Conley S., 2019, Effect of strip-till timing, fertilizer placement, and row spacing on soybean seed yield, Crop, Forage & Turfgrass Management, 5: 190040.
https://doi.org/10.2134/cftm2019.05.0040

Sichilima I., Mataa M., and Mweetwa, A.M., 2018, Morpho-physiological and yield responses associated with plant density variation in soybean (*Glycine max* L. Merrill), International Journal of Environment, Agriculture and Biotechnology, 3(1): 274-285.
https://doi.org/10.22161/ijeab/3.1.35

Szpunar-Krok E., Bobrecka-Jamro D., Pikuła W., and Jańczak-Pieniążek M., 2023, Effect of nitrogen fertilization and inoculation with *Bradyrhizobium japonicum* on nodulation and yielding of soybean, Agronomy, 13(5): 1341.
https://doi.org/10.3390/agronomy13051341

Wang J., Zhang J., Guo F., Yang S., Gao H., Zhang C., Zhao H., Li X., and Wan S., 2022, Band application of peanut-specific slow-release compound fertilizer at different soil depths promotes the root growth, yield performance and nitrogen utilization of peanut, Journal of Plant Nutrition and Fertilizers, 28(12): 2274-2286.
https://doi.org/10.11674/zwyf.2022148

Wysokinski A., Wysokińska A., Noulas C., and Wysokińska A., 2024, Optimal nitrogen fertilizer rates for soybean cultivation, Agronomy, 14(7): 1375. https://doi.org/10.3390/agronomy14071375

Xu C., Li R., Song W., Wu T., Sun S., Han T., and Wu C., 2021, High density and uniform plant distribution improve soybean yield by regulating population uniformity and canopy light interception, Agronomy, 11(9): 1880. https://doi.org/10.3390/AGRONOMY11091880

Xue Y., Zhang Y., Huang Q., and Wang Z.M., 2015, Effects of narrow row spacing and uniform sowing on canopy environment, individual plant traits and biomass production in late-sowing winter wheat, Acta Ecologica Sinica, 35(16): 5545-5555. https://doi.org/10.5846/stxb201402150258

Yang M., Han X., Xie J., Zhang S., Lv Z., Li B., Shi L., Zhang K., and Ge B., 2022, Field application of Wuyiencin against Sclerotinia stem rot in soybean, Frontiers in Sustainable Food Systems, 6: 930079. https://doi.org/10.3389/fsufs.2022.930079

Yanni A.E., Iakovidi S, Vasilikopoulou E, 2023, Legumes: a vehicle for transition to sustainability, Nutrients, 16(1): 98. https://doi.org/10.3390/nu16010098

Yoshihira T., Liang S., Suzuki H., Kitabatake T., and Shiraiwa T., 2020, Effects of maturity group and stem growth habit on the branching plasticity of soybean cultivars grown at various planting densities, Plant Production Science, 23(4): 385-396. https://doi.org/10.1080/1343943X.2020.1743187

Zhou H., Yao X., Zhao Q., Zhang W., Zhang B., and Xie F., 2019, Rapid effect of nitrogen supply for soybean at the beginning flowering stage on biomass and sucrose metabolism, Scientific Reports, 9: 52043. https://doi.org/10.1038/s41598-019-52043-6

Zhou H., Zhang M., Liu Z., Zheng W., Zhu Q., and Wan Y., 2019, Maize yield and economic return with controlled-release urea, Nutrient Cycling in Agroecosystems, 115: 427-440. https://doi.org/10.1007/s10705-019-10020-5