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The Role of Plant Density and Nutrient Management in Soybean Yield Optimization

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Abstract This study explores the role of plant density and nutrient management in optimizing soybean yield. High plant density significantly increases soybean productivity by enhancing canopy light interception and dry matter accumulation but may also lead to increased competition for resources. Low plant density helps improve individual plant growth and nutrient use efficiency, although the overall yield may slightly decrease. Nutrient management is crucial for soybean growth, with different growth stages requiring different nutrient needs. Proper nutrient supply and management strategies can enhance soybean's adaptability to environmental stresses, increase yield, and reduce input costs. This review proposes optimized strategies for the synergy between plant density and nutrient management to improve soybean productivity and sustainability.
Keywords Plant density; Nutrient management; Soybean yield; Canopy light interception; Resource use efficiency

1 Introduction

Soybean (*Glycine max*) is a critical crop in global agriculture, primarily valued for its high oil and protein content. It serves as a major source of vegetable oil and protein for both human consumption and animal feed. The efficient production of soybean is essential to meet the growing global demand for these nutrients (Bagale, 2021). The crop's ability to fix atmospheric nitrogen through symbiosis with *Bradyrhizobium* bacteria also makes it a valuable component in sustainable agricultural systems (Luca et al., 2014).

The optimization of soybean yield is increasingly challenged by climate change and the limited availability of arable land. Climate change impacts, such as altered precipitation patterns and increased temperatures, can adversely affect soybean growth and productivity (Dass et al., 2022). Additionally, the expansion of soybean cultivation into less suitable agro-climatic regions necessitates improved management practices to maintain yield levels (Adamič and Leskovšek, 2021). The limited arable land available for soybean cultivation further underscores the need for strategies that maximize yield per unit area (Assefa et al., 2019).

This study aims to explore how plant density and nutrient management can work together to optimize soybean yield. To investigate the interaction between these two factors provide insights into effective agricultural practices that can enhance soybean productivity. The study will cover various aspects of plant density, including its impact on inter-plant competition and canopy light interception, as well as the role of nutrient management in addressing deficiencies and improving resource-use efficiency. The ultimate goal is to identify practices that can sustainably increase soybean yield while minimizing input costs and environmental impacts.

2 Basics and Concepts of Soybean Plant Density

2.1 Definition and types of plant density

Plant density refers to the number of plants per unit area, which can significantly influence crop yield and quality. In soybean cultivation, plant density is typically categorized into high, low, and moderate densities. High-density planting involves a greater number of plants per hectare, which can enhance canopy light interception and dry matter accumulation, leading to increased productivity. For instance, a study demonstrated that higher planting density significantly increased soybean seed yield by 22.8% compared to normal planting density (Xu et al., 2021). Conversely, low-density planting reduces competition among plants for resources such as water, nutrients, and light, which can improve individual plant growth and nodulation parameters (Luca et al., 2014). Moderate density strikes a balance between these two extremes, aiming to optimize both yield and resource use efficiency.

Different planting densities can also affect the uniformity of plant distribution. Uniform plant spacing at high densities has been shown to reduce plant-to-plant variability and increase overall yield by 9.5% compared to non-uniform spacing (Xu et al., 2021). This highlights the importance of not just the number of plants but also their spatial arrangement in the field.

2.2 Methods of adjusting plant density

Adjusting plant density in soybean cultivation can be achieved through various methods, primarily by altering the spacing between plants and rows. Row spacing is a critical factor; narrower rows can increase canopy closure and light interception, which are beneficial for photosynthesis and yield. For example, a study found that reducing row spacing to 15 cm improved yield structure parameters and chlorophyll fluorescence in soybean plants (Table 1) (Jańczak-Pieniążek et al., 2021). On the other hand, wider row spacing can reduce competition for resources but may lead to lower overall yield.

Table 1 Effect of row spacing and sowing density on seed yield and structural yield components of soybean (Adopted from Jańczak-Pieniążek et al., 2021)

Factor		Seed yield (tha^{-1})	Number of pods per plant (pcs.)	Number of seeds per plant (pcs.)	Seed weight per plant (g)	Thousand seeds weight (g)
Row spacing (cm) (S)	Sowing density (pcs/m^{-2}) (D)					
15	70	4.84^{a}±0.54	27.6^{b}±9.5	57.0^{c}±10.6	8.23^{c}±1.27	146^{a}±18
	90	4.95^{a}±0.48	20.4^{ab}±4.5	45.1^{ab}±7.4	7.61^{c}±0.97	173b±39
	110	4.91^{a}±0.42	19.9^{a}±9.0	42.9^{a}±8.7	6.01^{ab}±1.05	142^{a}±18
30	70	4.73^{a}±0.48	24.6^{ab}±8.6	50.8^{bc}±9.6	7.82^{c}±0.99	157^{a}±23
	90	4.874^{a}±0.40	23.6^{ab}±5.8	45.4^{ab}±6.9	6.65^{b}±0.80	148^{a}±17
	110	4.85^{a}±0.35	18.5^{a}±5.4	41.0^{a}±9.0	5.75^{a}±1.17	141^{a}±12
15	-	4.90^{a}±0.47	22.6^{a}±8.5	48.3^{a}±10.8	7.28^{b}±1.43	154^{a}±30
30	-	4.82^{a}±0.41	22.2^{b}±7.1	45.7^{a}±9.3	6.74^{a}±1.29	148^{a}±19
-	70	4.78^{a}±0.50	26.1^{b}±9.0	53,9^{b}±10.4	8.02^{c}±1.13	151^{b}±21
-	90	4.91^{a}±0.43	22.0^{ab}±5.3	45.2^{a}±7.0	7.13^{b}±1.00	161^{c}±32
-	110	4.88^{a}±0.38	19.2^{a}±7.3	42.0^{a}±8.7	5.88^{a}±1.10	141^{a}±15
Year (Y)						
2017		4.51^{a}±0.30	20.1^{a}±4.2	42.64^{a}±9.1	5.98^{a}±1.35	140^{a}±5
2018		5.33^{c}±0.29	19.3^{a}±5.8	42.9^{a}±6.1	7.31^{b}±0.92	173^{b}±30
2019		4.74^{b}±0.22	27.9^{b}±9.4	55.5^{b}±8.8	7.74^{b}±1.22	140^{a}±14
Mean		4.86±0.44	22.4±7.8	47.0±10.0	7.01±1.38	151±25
S		ns	ns	ns	**	ns
D		ns	**	***	***	***
Y		***	***	***	***	***
S×D		ns	ns	ns	ns	***
S×Y		ns	ns	ns	ns	ns
D×Y		ns	ns	**	ns	**
S×D×Y		ns	ns	ns	ns	*

Table caption: The results are presented as mean values±standard deviation. Different letters in the same column indicate significant differences *p*=0.05), according to ANOVA followed by Tukey's test. *,**,*** and ns mean ≤005, ≤0.01, <0.001, and not significant, respectively (Adopted from Jańczak-Pieniążek et al., 2021)

The spacing between individual plants within rows is another method to adjust plant density. Uniform spacing can minimize competition and improve resource use efficiency. Research has shown that uniform plant distribution significantly increases canopy light interception and dry matter accumulation, leading to higher yields (Xu et al., 2021). Factors influencing the choice of plant density and spacing include soil fertility, water availability, and the specific soybean genotype being cultivated. For instance, different genotypes may respond differently to plant density adjustments, with some showing significant yield increases at higher densities while others may not (Gan et al., 2002; Wang et al., 2024).

2.3 Competition for space in crops

Competition for space among soybean plants primarily involves competition for water, light, and nutrients. High plant density can lead to intense competition for these resources, which can affect plant growth and yield. For example, increased plant density can enhance canopy light interception but may also lead to reduced individual plant growth due to competition for light (Xu et al., 2021). Similarly, competition for water and nutrients can be more intense at higher densities, potentially leading to nutrient deficiencies and reduced nodulation (Luca et al., 2014).

Mechanisms of competition include shading, which reduces light availability to lower leaves, and root competition, which limits water and nutrient uptake. Studies have shown that non-uniform temporal distributions of plants can significantly reduce yield due to increased variability in plant growth and reproductive partitioning (Masino et al., 2018). This suggests that managing plant density and ensuring uniform plant distribution are crucial for optimizing resource use and maximizing yield. Additionally, the choice of planting density can influence physiological responses such as leaf area ratio and specific leaf area, which in turn affect biomass production and yield (Gan et al., 2002).

3 Effects of Soybean Plant Density on Growth and Yield

3.1 Relationship between photosynthesis efficiency and plant density

Optimizing plant density is crucial for enhancing photosynthesis efficiency in soybean crops. Higher planting densities have been shown to significantly increase canopy light interception, which in turn boosts the photosynthetic rate and dry matter accumulation. For instance, a study demonstrated that increasing planting density from 1.8×10^5 to 2.7×10^5 plants ha^{-1} led to a 22.8% increase in seed yield due to improved light capture and uniform plant spacing (Xu et al., 2021). This indicates that optimal plant density can enhance the overall photosynthetic efficiency of the soybean canopy, thereby improving yield.

Moreover, lower plant densities can also have a positive impact on photosynthesis by reducing inter-plant competition for light, water, and nutrients. A study conducted in southern Brazil found that reducing plant density to 80 000 plants ha^{-1} increased nodulation and photosynthesis per plant, although the overall yield was slightly reduced in one of the three cropping seasons (Luca et al., 2014). This suggests that while higher densities improve canopy-level photosynthesis, lower densities can enhance individual plant photosynthesis efficiency.

3.2 Changes in plant morphological characteristics

Plant density significantly affects the morphological characteristics of soybean plants, including plant height, branch number, and leaf area index (LAI). Higher plant densities generally lead to taller plants with fewer branches and a higher LAI. For example, a study found that increasing plant density resulted in taller plants but reduced the number of branches per plant, which can affect the overall yield components (Moreira et al., 2015). This morphological adjustment is a response to increased competition for light, prompting plants to grow taller to capture more sunlight.

Conversely, lower plant densities allow for more branching and a lower LAI, which can be beneficial for certain growth stages. Another study highlighted that lower densities resulted in increased nodulation and biomass production per plant, although the total yield per hectare was lower compared to higher densities (Luca and Hungria, 2014). This indicates that while higher densities optimize light capture and photosynthesis at the canopy level, lower densities can enhance individual plant growth and development.

3.3 Density effects on yield performance

Balancing group competition and individual plant yield is a critical aspect of optimizing soybean yield under varying plant densities. Higher plant densities often lead to increased competition among plants, which can reduce the yield per individual plant but increase the overall yield per unit area. For instance, a study reported that higher plant densities significantly increased the field biomass yield and seed yield per unit area, despite reducing the yield per individual plant (Gonyane and Sebetha, 2021). This suggests that higher densities can maximize total yield by optimizing space utilization and light interception.

However, extremely high densities can lead to excessive competition, negatively impacting both individual plant yield and overall productivity. A study found that while increasing plant density generally improved yield, densities beyond a certain threshold (e.g., 100 plants m^{-2}) resulted in reduced seed yield due to excessive competition (Rahman et al., 2011). Therefore, finding the optimal balance between plant density and competition is essential for maximizing soybean yield.

4 Role of Nutrient Management in Soybean Growth

4.1 Key nutrient requirements for soybean

Soybean plants require a balanced supply of essential nutrients to achieve optimal growth and yield. The primary macronutrients necessary for soybean development include nitrogen (N), phosphorus (P), and potassium (K). Nitrogen is crucial for protein synthesis and overall plant growth. It can be supplied through biological nitrogen fixation (BNF) or mineral fertilizers. However, excessive nitrogen fertilization can reduce BNF by up to 70% in greenhouse conditions and 44% in field conditions, particularly during the vegetative stage (Santachiara et al., 2019). Phosphorus is vital for energy transfer and root development, while potassium is essential for enzyme activation and water regulation. Studies have shown that soybean plants accumulate significant amounts of these nutrients, with 275 kg N, 21 kg P, and 172 kg K required per hectare to produce high yields (Bender et al., 2015).

In addition to macronutrients, soybean plants also need micronutrients such as zinc (Zn), boron (B), and molybdenum (Mo). These micronutrients play critical roles in various physiological processes. For instance, foliar application of Zn and B has been shown to significantly improve pod formation and seed yield in semi-arid climates (Dass et al., 2022). The omission of these nutrients can lead to visible deficiency symptoms and reduced plant growth, as observed in nutrient omission trials in Western Kenya (Keino et al., 2015).

4.2 Nutrient management in different growth stages of soybean

The nutrient demands of soybean plants vary significantly across different growth stages, including germination, flowering, and pod-filling stages. During the germination stage, the primary focus is on root development and early vegetative growth, which requires adequate phosphorus and potassium. Studies have shown that phosphorus and potassium uptake is critical during the early vegetative stages, with up to 100% of season-long potassium uptake occurring by the R5.5 stage (Gaspar et al., 2017).

As the plants transition to the flowering stage, the demand for nitrogen increases to support rapid vegetative growth and the initiation of reproductive structures. Nitrogen fertilization during this stage can significantly improve shoot dry weights and overall plant biomass (Keino et al., 2015). However, excessive nitrogen application during the vegetative stage can reduce BNF, highlighting the need for balanced nutrient management (Santachiara et al., 2019).

During the pod-filling stage, the nutrient demand shifts towards supporting seed development. This stage requires a continuous supply of nitrogen, phosphorus, and potassium to ensure high seed yield and quality. Studies have shown that foliar application of nutrients such as urea, NPK, and DAP during the pod initiation stage can significantly improve seed yield and water-use efficiency (Dass et al., 2022). Additionally, adequate irrigation during this stage is crucial for nutrient uptake and overall plant health.

4.3 Nutrient management strategies

Effective nutrient management strategies for soybean cultivation involve the application of both organic and inorganic fertilizers. Organic fertilizers, such as cattle bone meal hydrolysate, have been shown to improve soybean growth characteristics, nutrient content, and chlorophyll pigment concentration (Nieto-Monteros et al., 2023). These organic sources provide a slow-release form of nutrients, enhancing soil fertility and reducing dependency on synthetic fertilizers.

Inorganic fertilizers, including urea, DAP, and NPK, are commonly used to meet the immediate nutrient demands of soybean plants. Foliar application of these fertilizers at critical growth stages, such as pod initiation, has been shown to significantly improve seed yield and economic returns (Dass et al., 2022). Additionally, the use of micronutrient supplements, such as zinc and boron, can further enhance plant growth and productivity (Keino et al., 2015).

Combining organic and inorganic fertilizers can provide a balanced nutrient supply, improving nutrient use efficiency and reducing environmental impact. For instance, a study on nutrient uptake and partitioning in modern soybean varieties highlighted the importance of adequate nutrient availability during key growth periods, emphasizing the need for integrated nutrient management strategies (Bender et al., 2015). By adopting these strategies, soybean farmers can achieve higher yields and sustainable production.

5 Interaction between Soybean Plant Density and Nutrient Management

5.1 Impact of density on nutrient uptake

Increased nutrient competition at high density can significantly affect nutrient uptake in soybean plants. High plant density often leads to increased competition for essential nutrients such as nitrogen, phosphorus, and potassium, which can limit the availability of these nutrients to individual plants. For instance, a study found that higher planting densities resulted in increased canopy light interception and dry matter accumulation, which in turn led to higher nutrient uptake and improved soybean productivity (Xu et al., 2021). However, this increased competition can also lead to nutrient deficiencies if the soil nutrient levels are not adequately managed. Another study highlighted that while higher plant densities increased the total dry matter production, it did not necessarily translate to higher grain yields unless nutrient management was optimized (Purucker and Steinke, 2020).

Lower plant densities, on the other hand, can reduce inter-plant competition for nutrients, thereby improving nutrient uptake efficiency. Research has shown that lower plant densities can lead to better nodulation and nitrogen fixation, which are crucial for soybean growth and yield. For example, a study conducted in southern Brazil demonstrated that lower plant densities resulted in increased nodulation parameters and improved plant nutritional status, although the overall yield was slightly reduced in one of the three cropping seasons (Luca et al., 2014). This suggests that while lower densities can enhance nutrient uptake, they may require careful management to avoid yield penalties.

5.2 Synergistic effects of nutrient use efficiency and density

Fertilizer efficiency under different density conditions can vary significantly, and understanding this interaction is crucial for optimizing soybean yield. Studies have shown that the application of fertilizers can enhance nutrient uptake and yield, but the effectiveness of these applications can depend on the planting density. For instance, a study found that applying a combination of mineral fertilizers and organic amendments at different planting densities significantly improved nutrient uptake and yield. This indicates that nutrient use efficiency can be maximized by adjusting fertilizer applications based on plant density.

Moreover, research has demonstrated that higher planting densities can improve the efficiency of nutrient use by increasing the early-season dry matter accumulation, which supports greater nutrient uptake and grain yield potential (Purucker and Steinke, 2020). Another study highlighted that the application of specific fertilizers, such as monoammonium phosphate combined with zinc sulfate, at different planting densities resulted in higher seed mass and improved yield parameters (Gonyane and Sebetha, 2021). These findings suggest that there is a synergistic effect between nutrient use efficiency and plant density, where optimal fertilization strategies can enhance the benefits of higher planting densities.

5.3 Impact of plant density on nutrient management

How to adjust fertilization based on plant density is a critical aspect of soybean cultivation. High plant densities require more precise nutrient management to ensure that all plants receive adequate nutrients. Studies have shown that higher planting densities can lead to increased nutrient uptake, but this also means that the soil nutrient levels need to be carefully monitored and managed. For example, a study found that higher planting densities required more frequent and targeted fertilizer applications to maintain optimal nutrient levels and avoid deficiencies (Purucker and Steinke, 2020).

Conversely, lower plant densities can benefit from reduced fertilizer inputs, as the competition for nutrients is less intense. Research has indicated that lower plant densities can achieve adequate nutrient uptake with lower fertilizer rates, thereby reducing input costs and minimizing environmental impacts. For instance, a study demonstrated that lower plant densities combined with efficient nutrient management practices, such as the use of organic amendments and biological nitrogen fixation, resulted in improved nutrient uptake and yield (Luca et al., 2014). This suggests that adjusting fertilization strategies based on plant density can lead to more sustainable and cost-effective soybean production.

6 Strategies for Optimizing Soybean Plant Density and Nutrient Management

6.1 Site-specific management approaches

Choosing optimal plant density and nutrient management strategies tailored to specific soil and climate conditions is crucial for maximizing soybean yield. Research indicates that higher planting densities can significantly enhance canopy light interception and dry matter accumulation, leading to increased soybean productivity. For instance, a study demonstrated that a higher planting density of 2.7×10^5 plants ha^{-1} resulted in a 22.8% increase in seed yield compared to a normal planting density, primarily due to improved canopy light interception and uniform plant distribution (Xu et al., 2021). Additionally, site-specific nutrient management, such as the optimal application of nitrogen, phosphorus, and potassium, can further enhance yield. In Northeast China, the optimal planting density was found to be 45.37×10^4 plants/ha with specific nutrient applications, resulting in yields of up to 3 816.67 kg/ha (Hao et al., 2023).

Moreover, the delineation of site-specific nutrient management zones using multivariate analysis and geostatistics can provide a practical and cost-effective approach to managing spatial soil fertility. This method allows for the identification of management zones within a field, optimizing nutrient application and improving yield outcomes. For example, a study in Brazil used principal component analysis and the fuzzy k-means algorithm to delineate management zones, resulting in a significant correlation between these zones and soybean yield (Martins et al., 2020). This approach ensures that nutrient management is tailored to the specific needs of different areas within a field, enhancing overall productivity.

6.2 Matching cultivar characteristics with management

Different soybean cultivars have varying responses to plant density and nutrient regimes, making it essential to match cultivar characteristics with appropriate management practices. For instance, a study on soybean cultivar BRS 284 revealed that lower plant densities increased nodulation parameters and seed oil content, although protein content decreased slightly. Despite a 75% reduction in plant density, yield only decreased by 16% in one of the three cropping seasons, indicating the high plasticity of this cultivar to adapt to different densities (Luca et al., 2014). This suggests that selecting cultivars with high adaptability to varying densities can optimize yield without compromising plant health.

Furthermore, the interaction between cultivar characteristics and nutrient management is critical. Research has shown that foliar application of macro- and micronutrients, such as zinc and boron, can significantly improve soybean yield and resource-use efficiency in semi-arid climates. For example, foliar-applied chelated zinc at 0.5% concentration increased seed yield by 18.5-37.8% compared to no foliar nutrition, highlighting the importance of matching nutrient management strategies with cultivar needs (Dass et al., 2022). This approach ensures that the specific nutrient requirements of different cultivars are met, optimizing growth and yield.

6.3 Integrated management and precision agriculture

Utilizing precision agriculture technologies to optimize plant density and fertilization can significantly enhance soybean yield. Precision agriculture involves the use of advanced technologies, such as GPS and remote sensing, to monitor and manage crop production at a fine scale. For instance, the use of variable rate fertilization based on site-specific nutrient management zones can optimize nutrient application, reducing waste and improving yield. A study demonstrated that the delineation of management zones using geostatistics and principal component analysis resulted in a significant correlation between these zones and soybean yield, indicating the effectiveness of precision agriculture in nutrient management (Martins et al., 2020).

Additionally, integrating precision agriculture with traditional management practices can further enhance yield outcomes. For example, research has shown that uniform plant distribution and higher planting densities can improve canopy light interception and dry matter accumulation, leading to increased productivity. By using precision agriculture technologies to ensure uniform plant spacing and optimal density, farmers can achieve higher yields without increasing other farm inputs (Xu et al., 2021). This integrated approach combines the benefits of advanced technology with proven agronomic practices, optimizing soybean production.

7 Current Challenges and Research Progress in Soybean Cultivation

7.1 Potential issues with high-density planting

High-density planting in soybean cultivation can lead to poor ventilation within the crop canopy, which in turn increases the risk of pest infestations and disease outbreaks. For instance, a study conducted in northeastern China found that while higher planting densities can optimize yield, they also create conditions conducive to pest and disease proliferation due to reduced air circulation (Hao et al., 2023). Similarly, research in southern Brazil indicated that lower plant densities could mitigate these risks by improving plant health and reducing stress factors such as competition for light and nutrients (Luca et al., 2014).

Moreover, high-density planting can exacerbate issues related to plant lodging, where plants fall over due to weak stems or adverse weather conditions. This is particularly problematic in regions with high rainfall or strong winds, as observed in southwestern Japan, where higher plant densities led to increased lodging and subsequent yield losses (Matsuo et al., 2018). Therefore, while high-density planting can enhance yield potential, it necessitates careful management to mitigate associated risks.

7.2 Complexity of nutrient management

Nutrient management in soybean cultivation is complex due to the varying nutrient requirements under different growth environments. For example, a study on soybean-wheat intercropping systems highlighted that different nitrogen application rates and planting densities significantly affected soybean yield and nutrient uptake (Moreira et al., 2015). This complexity is further compounded by the need to balance macronutrients and micronutrients, as demonstrated in a study that found foliar application of nutrients like zinc and boron significantly improved soybean yield and quality in semi-arid climates (Dass et al., 2022).

Additionally, nutrient partitioning within the plant is influenced by environmental conditions and management practices. Research has shown that nutrient uptake and distribution are critical for optimizing yield, with specific nutrient ratios being essential for different growth stages (Tamagno et al., 2017). This underscores the need for tailored nutrient management strategies that consider the unique requirements of each growing environment.

7.3 Current research gaps and limitations

Despite significant advancements, there remain gaps in research on the interaction between planting density and nutrient management in soybean cultivation. For instance, while studies have explored the effects of individual factors such as planting density or nutrient application, there is limited research on their combined impact on yield and plant health (Xu et al., 2021). This gap is evident in the lack of comprehensive studies that integrate both aspects to provide holistic management recommendations.

Furthermore, existing research often focuses on specific regions or conditions, limiting the generalizability of findings. For example, studies conducted in northeastern China and southern Brazil provide valuable insights but may not be directly applicable to other regions with different climatic and soil conditions (Luca et al., 2014; Hao et al., 2023). Therefore, more research is needed to develop universally applicable guidelines that consider the diverse environments in which soybeans are cultivated.

8 Future Research Directions in Soybean Plant Density and Nutrient Management

8.1 New approaches to improve fertilizer use efficiency

The development of slow-release fertilizers and smart fertilization technologies is crucial for enhancing fertilizer use efficiency in soybean cultivation. Slow-release fertilizers, such as those containing polysulfide matrices with dispersed struvite, have shown promise in providing sustained nutrient delivery, which can significantly improve root system development and overall plant biomass. For instance, the use of struvite-based fertilizers resulted in up to three times higher shoot mass and ten times higher root mass compared to traditional fertilizers, highlighting their potential in optimizing nutrient uptake and improving yield (Valle et al., 2022). Additionally, the foliar application of micronutrients like zinc and boron has been demonstrated to enhance water-use efficiency and production efficiency, suggesting that integrating these approaches with slow-release fertilizers could further boost soybean productivity (Dass et al., 2022).

Smart fertilization technologies, including the use of the Normalized Difference Vegetation Index (NDVI) for real-time monitoring of plant nutrient status, offer another avenue for improving fertilizer use efficiency. NDVI has been effectively used to estimate soybean biomass and nutrient uptake, providing farmers with a tool to assess spatial variability in crop growth and adjust fertilization strategies accordingly (Farias et al., 2023). Future research should focus on integrating these technologies with slow-release fertilizers to develop comprehensive nutrient management systems that maximize yield while minimizing environmental impact.

8.2 Dynamic adjustment of plant density based on environment

Optimizing plant density in response to changing environmental conditions is essential for maintaining high soybean yields. Climate change poses significant challenges to traditional planting strategies, necessitating dynamic adjustments to plant density to ensure optimal light interception, water use, and nutrient uptake. Studies have shown that higher planting densities can significantly increase canopy light interception and dry matter accumulation, leading to improved soybean productivity (Xu et al., 2021). However, the benefits of higher densities must be balanced against the risk of increased competition for resources, particularly under variable climatic conditions.

Research has also indicated that uniform plant distribution can enhance yield by reducing plant-to-plant variability and improving canopy light interception (Xu et al., 2021). This suggests that future studies should explore the potential of adaptive planting strategies that adjust density and distribution patterns based on real-time environmental data. Additionally, the feasibility of lowering planting density without compromising yield, as demonstrated in some studies, should be further investigated to develop flexible planting guidelines that can be tailored to specific climatic scenarios (Luca et al., 2014).

8.3 New cultivars and response to density-nutrient interactions

Breeding high-yield soybean cultivars that are well-suited to high-density planting and responsive to nutrient management practices is a critical area for future research. The interaction between plant density and nutrient availability can significantly influence soybean yield and quality. For example, studies have shown that lower plant densities can enhance nodulation and nitrogen fixation, which are vital for maintaining soil fertility and crop productivity (Luca et al., 2014; Wang, 2024). Conversely, higher densities may require cultivars with improved nutrient uptake efficiency to mitigate the effects of increased competition.

The development of new soybean cultivars should focus on traits that enhance their adaptability to varying plant densities and nutrient conditions. This includes breeding for improved root architecture, which can facilitate better nutrient uptake and support higher planting densities (Valle et al., 2022). Additionally, the response of different cultivars to foliar nutrient applications, such as zinc and boron, should be explored to identify those that can maximize yield under specific nutrient management regimes (Dass et al., 2022). By integrating these breeding efforts with advanced nutrient management practices, it will be possible to develop soybean production systems that are both high-yielding and sustainable.

9 Concluding Remarks

The optimization of soybean yield is significantly influenced by both plant density and nutrient management. Higher planting densities have been shown to increase canopy light interception and dry matter accumulation, leading to improved soybean productivity. For instance, a study demonstrated that increasing planting density resulted in a 22.8% higher seed yield compared to normal planting density, and uniform plant spacing further enhanced yield by 9.5%. Additionally, nutrient management, particularly nitrogen application, plays a crucial role in yield optimization. In arid regions, the optimal combination of nitrogen, phosphorus, and potassium fertilizers was found to significantly enhance grain yield and biomass. Therefore, the appropriate combination of plant density and nutrient management is essential to achieve maximum soybean yield.

Achieving optimal soybean yield requires a comprehensive approach that considers plant density, nutrient management, and environmental factors. Studies have shown that soybean plants exhibit high plasticity, adapting their photosynthesis and nitrogen fixation to different plant densities, which can mitigate the effects of environmental and nutritional stresses. Moreover, the interaction between row spacing, plant density, and nitrogen fertilization has been found to influence various physiological and yield components in soybean-wheat intercropping systems. Therefore, a multi-factor collaborative management strategy that integrates these elements is necessary to optimize soybean yield under varying environmental conditions.

For practical agricultural applications, farmers and producers should adopt strategies that optimize both planting and fertilization practices. For instance, reducing plant density can lower input costs and reduce susceptibility to environmental stresses without significantly compromising yield. Additionally, ensuring uniform plant distribution and optimal fertilization can enhance yield without increasing other farm inputs. Practical guidelines derived from research, such as the optimal fertilization levels for different regions and the benefits of early planting and stress minimization, can help farmers achieve higher yields. By implementing these strategies, farmers can improve soybean productivity and sustainability in their agricultural practices.

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References
Adamič S., and Leskovšek R., 2021, Soybean (*Glycine max* (L.) Merr.) growth, yield, and nodulation in the early transition period from conventional tillage to conservation and no-tillage systems, Agronomy, 11(12): 2477.
https://doi.org/10.3390/agronomy11122477

Assefa Y., Purcell L., Salmerón M., Naeve S., Casteel S., Kovács P., Archontoulis S., Licht M., Below F., Kandel H., Lindsey L., Gaska J., Conley S., Shapiro C., Orlowski J., Golden B., Kaur G., Singh M., Thelen K., Laurenz R., Davidson D., and Ciampitti I., 2019, Assessing variation in US soybean seed composition (protein and oil), Frontiers in Plant Science, 10: 298.
https://doi.org/10.3389/fpls.2019.00298

Bagale S., 2021, Nutrient management for soybean crops, International Journal of Agronomy, 2021(1): 3304634.
https://doi.org/10.1155/2021/3304634

Bender R., Haegele J., and Below F., 2015, Nutrient uptake, partitioning, and remobilization in modern soybean varieties, Agronomy Journal, 107: 563-573.
https://doi.org/10.2134/AGRONJ14.0435

Dass A., Rajanna G., Babu S., Lal S., Choudhary A., Singh R., Rathore S., Kaur R., Dhar S., Singh T., Raj R., Shekhawat K., Singh C., and Kumar B., 2022, Foliar application of macro- and micronutrients improves the productivity, economic returns, and resource-use efficiency of soybean in a semiarid climate, Sustainability, 14(10): 5825.
https://doi.org/10.3390/su14105825

Echarte L., Maggiora A., Cerrudo D., Gonzalez V., Abbate P., Cerrudo A., Sadras V., and Calviño P., 2011, Yield response to plant density of maize and sunflower intercropped with soybean, Field Crops Research, 121: 423-429.
https://doi.org/10.1016/J.FCR.2011.01.011

Farias G., Bremm C., Bredemeier C., Menezes J., Alves L., Tiecher T., Martins A., Fioravanço G., Silva G., and Carvalho P., 2023, Normalized Difference Vegetation Index (NDVI) for soybean biomass and nutrient uptake estimation in response to production systems and fertilization strategies, Frontiers in Sustainable Food Systems, 6: 959681.
https://doi.org/10.3389/fsufs.2022.959681

Ferreira A., Junior A., Werner F., Zucareli C., Franchini J., and Debiasi H., 2016, Plant density and mineral nitrogen fertilization influencing yield, yield components and concentration of oil and protein in soybean grains, Bragantia, 75: 362-370.
https://doi.org/10.1590/1678-4499.479

Gan Y., Stulen I., Keulen H., and Kuipe, P., 2002, Physiological response of soybean genotypes to plant density, Field Crops Research, 74: 231-241.
https://doi.org/10.1016/S0378-4290(01)00212-X

Gaspar A., Laboski C., Naeve S., and Conley S., 2017, Phosphorus and potassium uptake, partitioning, and removal across a wide range of soybean seed yield levels, Crop Science, 57: 2193-2204.
https://doi.org/10.2135/CROPSCI2016.05.0378

Gonyane M., and Sebetha E., 2021, The effect of plant density, zinc added to phosphorus fertilizer sources and location on selected yield parameters of soybean, Legume Research-An International Journal, 45(2): 196.
https://doi.org/10.18805/lrf-647

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

Jańczak-Pieniążek M., Buczek J., Bobrecka-Jamro D., Szpunar-Krok E., Tobiasz-Salach R., and Jarecki W., 2021, Morphophysiology, productivity and quality of soybean (*Glycine max* (L.) Merr.) cv. merlin in response to row spacing and seeding systems, Agronomy, 11(2): 403.
https://doi.org/10.3390/AGRONOMY11020403

Keino L., Baijukya F., Ng'etich W., Otinga A., Okalebo J., Njoroge R., and Mukalama J., 2015, Nutrients limiting soybean (*Glycine max* L.) Growth in acrisols and ferralsols of western Kenya, PLoS One, 10(12): e0145202.
https://doi.org/10.1371/journal.pone.0145202

Luca M., and Hungria M., 2014, Plant densities and modulation of symbiotic nitrogen fixation in soybean, Scientia Agricola, 71: 181-187.
https://doi.org/10.1590/S0103-90162014000300002

Luca M., Nogueira M., and Hungria M., 2014, Feasibility of lowering soybean planting density without compromising nitrogen fixation and yield, Agronomy Journal, 106: 2118-2124.
https://doi.org/10.2134/AGRONJ14.0234

Mangaraj S., Malligawad L., Paikaray R., Pradhan S., and Sahoo T., 2018, Impact of different ratios and levels of nitrogen and phosphorus on growth, yield and nutrient uptake of rainfed soybean, Legume Research, 41: 861-866.
https://doi.org/10.18805/LR-3819

Martins R., Valente D., Rosas J., Santos F., Santos F., Nascimento M., and Nascimento A., 2020, Site-specific nutrient management zones in soybean field using multivariate analysis: an approach based on variable rate fertilization, Communications in Soil Science and Plant Analysis, 51: 687-700.
https://doi.org/10.1080/00103624.2020.1729793

Masino A., Rugeroni P., Borrás L., and Rotundo J., 2018, Spatial and temporal plant-to-plant variability effects on soybean yield, European Journal of Agronomy, 98: 14-24.
https://doi.org/10.1016/J.EJA.2018.02.006

Matsuo N., Yamada T., Takada Y., Fukami K., and Hajika M., 2018, Effect of plant density on growth and yield of new soybean genotypes grown under early planting condition in southwestern Japan, Plant Production Science, 21: 16-25.
https://doi.org/10.1080/1343943X.2018.1432981

Moreira A., Moraes L., Schroth G., and Mandarino J., 2015, Effect of nitrogen, row spacing, and plant density on yield, yield components, and plant physiology in soybean–wheat intercropping, Agronomy Journal, 107: 2162-2170.
https://doi.org/10.2134/AGRONJ15.0121

Nieto-Monteros D., Penha R., and Soccol C., 2023, Foliar supplementation of recycled phosphorus from cattle bone meal improves soybean growth characteristics, nutrient content, and chlorophyll pigment concentration, Sustainability, 15(8): 6582.
https://doi.org/10.3390/su15086582

Purucker T., and Steinke K., 2020, Soybean seeding rate and fertilizer effects on growth, partitioning, and yield, Agronomy Journal, 112(3): 2288-2301.
https://doi.org/10.1002/agj2.20208

Rahman M., Hossain M., Anwar M., and Juraimi A., 2011, Plant density influence on yield and nutritional quality of soyabean seed, Asian Journal of Plant Sciences, 10: 125-132.
https://doi.org/10.3923/AJPS.2011.125.132

Santachiara G., Salvagiotti F., and Rotundo J., 2019, Nutritional and environmental effects on biological nitrogen fixation in soybean: a meta-analysis, Field Crops Research, 240: 106-115.
https://doi.org/10.1016/J.FCR.2019.05.006

Setubal I., Júnior A., Silva S., Rodrigues A., Bonifácio A., Silva E., Vieira P., Mirand, R., Menza N., and Souza H., 2023, Macro and micro-nutrient accumulation and partitioning in soybean affected by water and nitrogen supply, Plants, 12(9): 1898.
https://doi.org/10.3390/plants12091898

Tamagno S., Balboa G., Assefa Y., Kovács P., Casteel S., Salvagiotti F., García F., Stewart W., and Ciampitti I., 2017, Nutrient partitioning and stoichiometry in soybean: a synthesis-analysis, Field Crops Research, 200: 18-27.
https://doi.org/10.1016/J.FCR.2016.09.019

Valle S., Giroto A., Guimarães G., Nagel K., Galinski A., Cohnen J., Jablonowski N., and Ribeiro C., 2022, Co-fertilization of sulfur and struvite-phosphorus in a slow-release fertilizer improves soybean cultivation, Frontiers in Plant Science, 13: 861574.
https://doi.org/10.3389/fpls.2022.861574

Wang X.M., Zong C.M., Qi Y.X., Sun G.H., Liu C.Y., and Wang Y.P., 2024, Translational genomics in legumes: enhancing crop resilience and yield, Legume Genomics and Genetics, 15(5): 244-256.
https://doi.org/10.5376/lgg.2024.15.0024

Wang Y., 2024, GWAS reveals progress in genes related to rice yield and quality, Rice Genomics and Genetics, 15(2): 48-57.
https://doi.org/10.5376/rgg.2024.15.0006

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