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Optimizing Planting Density and Row Configuration to Improve Cotton Yield and Fiber Quality

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Abstract Cotton, as a globally significant economic crop, its yield and fiber quality are directly related to the textile industry and farmers' income. Planting density and row spacing configuration are key cultivation factors that affect the population structure, light energy utilization efficiency and yield and quality formation of cotton. This study reviews the regulatory effects of planting density on the photosynthetic efficiency, boll formation characteristics and fiber traits of cotton, explores the mechanism of row spacing configuration in improving population structure, root distribution and fiber consistency, and focuses on analyzing the interaction effect between density and row spacing. On this basis, combined with practical cases from typical regions (the Yellow River Basin in China, the southern United States and the cotton-growing areas in Central Asia), The application experience of optimizing density and row spacing under different ecological conditions was summarized. This study also focused on molecular and physiological mechanisms such as photosynthetic gene expression, hormone regulation, and root-crown coordination, providing theoretical support for a deeper understanding of the relationship between cultivation measures and fiber quality formation. This study aims to provide a reference path for the development of precise cultivation models and smart agriculture, promoting the coordinated improvement of cotton yield and fiber quality.
Keywords Cotton; Planting density; Line spacing configuration; Output; Fiber quality

1 Introduction

Cotton (*Gossypium* spp.) is a very important crop, and humans have been cultivating it for thousands of years. It is the main source of natural fibers in the textile industry and also provides jobs and income for millions of people around the world. China is one of the major cotton-producing countries in the world and also an important exporter of textiles. Cotton holds a very important position in China's national economy. Nowadays, people have increasingly higher demands for cotton. They not only hope for good fiber quality but also expect more efficient and environmentally friendly cultivation methods. Therefore, improving the cultivation methods of cotton becomes particularly important to meet the needs of industrial development and economic growth (Wang et al., 2019).

Planting density and row spacing are the key factors influencing cotton yield and fiber quality. They will alter the canopy structure, the utilization of light, photosynthetic efficiency and the allocation of resources within the plant. High-density planting can usually increase the yield of lint cotton by increasing the number of cotton bolls per unit area, but the competition for light and nutrients is also more intense, which may lead to a decrease in the weight of single bolls and a reduction in fiber quality parameters such as strength and Macron value (Stephenson et al., 2011; Goren and Tan, 2024). On the contrary, low-density planting is beneficial to fiber quality, but the total output may decline (Zhi et al., 2016; Cordeiro et al., 2022). The configuration of row spacing, such as equal rows, narrow rows or double rows, can also affect the canopy structure, light distribution and leaf drop efficiency. Some models can increase output and also improve the quality of mechanical harvesting (Wang et al., 2024). However, the optimal combination of density and row spacing varies in different regions, varieties and environmental conditions. When the density is too high, it may lead to a decrease in output and a deterioration in fiber quality. Although domestic and international research has made much progress in exploring the best planting model, how to balance yield, quality and resource utilization efficiency in different environments remains a challenge (Galdi et al., 2022).

This study reviewed the effects of planting density and row spacing on cotton yield and fiber quality, and sorted out the latest research results at home and abroad. The article analyzes the physiological and agronomic mechanisms behind these influences, compares the performance of various densities and planting methods under different environmental and management conditions, and also puts forward some suggestions for optimizing cotton cultivation. This study aims to provide some practical ideas for growers, ensuring yield while also enhancing fiber quality and improving overall economic benefits.

2 Effects of Planting Density on Cotton Yield and Quality

2.1 Regulation of photosynthetic efficiency and canopy structure under different planting densities

Planting density has a significant impact on the canopy structure of cotton and also alters light interception, photosynthetic efficiency and the microclimate in the field. Moderate or high density can increase the leaf area index (LAI), allowing reproductive organs to obtain more light energy and accumulate more biomass, thereby enhancing yield. However, if the density is too high, the canopy will close prematurely, and the lower leaves will not receive sufficient light, intensifying the competition for resources. The result may be a decrease in photosynthetic efficiency and premature senescence of the leaves (Yang et al., 2014; Khan et al., 2017). Appropriate density can maintain balance, ensure reasonable light distribution and suitable canopy temperature, which is conducive to efficient photosynthesis and normal growth (Khan et al., 2020).

2.2 Effects of density on boll distribution and fruiting characteristics

When the planting density increases, the number of cotton bolls per mu will be greater, but the number of cotton bolls on each plant will decrease, and the weight of each boll will also drop. High density is conducive to the rapid closure of the canopy, and the plants mature earlier. However, the competition is also more intense, and the cotton bolls will become smaller and concentrate on the upper and distal branches. When the density is low, the plants have more branches, more cotton bolls per plant, and larger cotton bolls. However, due to the smaller number of plants, the total yield may decrease (Li et al., 2020). An appropriate density can optimize the number of cotton bolls and the growth rate of fruits, which is directly related to the total output.

2.3 Relationship between planting density and fiber quality traits

Different fiber quality properties respond differently to density. Higher density generally increases the yield of lint cotton, but due to intensified competition and changes in sucrose metabolism, the fiber strength, Macron value (fineness), and maturity may decline (Jalilian et al., 2023). At medium to high densities, the fiber length may be slightly longer, but at low densities, the strength and fineness of the fibers are often better. The role of genotype in fiber quality is also quite obvious, and reasonable density management helps to maintain or even enhance quality potential. If the density is too high, it will also reduce the activity of sucrose synthase and the cellulose content in the fiber, resulting in a decrease in the Macron value and maturity (Meng et al., 2016; Zhang and Wang, 2024).

3 Mechanisms of Row Configuration

3.1 Effects of wide-narrow row configuration on canopy structure, ventilation and light interception

Different row spacing arrangements can alter the structure of the cotton canopy and also affect the lighting and ventilation conditions. Both wide and narrow line spacing (such as 66+10 cm) and uniform line spacing (such as 76 cm) can have a significant impact. High-density and wide-narrow rows can enable the canopy to absorb more photosynthetically active radiation (PAR), resulting in higher photosynthetic efficiency and an increase in the biomass of cotton bolls, especially during the critical growth period of cotton. However, if uniform row spacing is combined with appropriate density, light can more easily penetrate to the middle and lower layers of the canopy, and both the leaf area index (LAI) and the overall photosynthesis of the canopy (CAP) will increase. This not only benefits the development of the lower cotton bolls but also improves the quality of the fibers. Under reasonable irrigation conditions, it can also ensure a relatively high yield (Hu et al., 2021). In addition, equal row spacing can also increase the light transmittance in the middle and upper layers, making the fruit branches grow more evenly and the distribution of cotton bolls more reasonable (Figure 1) (Gao et al., 2024).

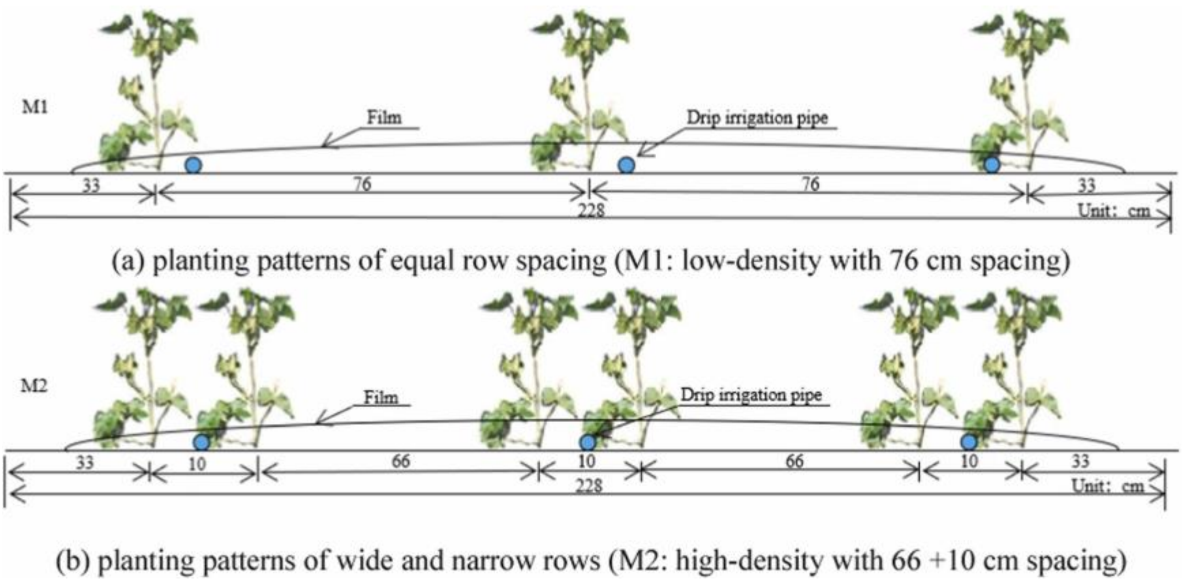

Figure 1 Schematic diagram of different planting patterns of machine-harvested cotton (Adopted from Gao et al., 2024)

3.2 Relationship between row spacing, root distribution, and nutrient use efficiency

Row spacing not only affects the growth of the above-ground part of cotton, but also influences the distribution of the underground root system. This will affect the cotton's ability to absorb water and nutrients. If the row spacing is uniform, the root system will be distributed more evenly, and there will be less competition among the plants, which can help cotton absorb more water and nutrients. However, if the rows are wide or narrow, the root systems may be concentrated in certain areas. In this way, the water and nutrients in these areas of the soil will be used up very quickly. Research has found that when uniform row spacing is combined with appropriate density, the water use efficiency (WUE) of cotton is the highest, especially at high density, the effect is more obvious. If wide and narrow rows are used but planted sparsely, the plants will not compete too much for water and nutrients, allowing the root system to extend more fully and also improving the WUE. This approach is particularly useful in cases of water shortage]. In addition, in the case of drip irrigation, the difference brought by this row spacing will be more obvious. Because drip irrigation can precisely water and fertilize based on the distribution of roots, its efficiency will be higher.

3.3 Influence of row configuration on fiber maturity and uniformity

The design of line spacing can also change the maturity and consistency of cotton fibers by influencing the microclimate of the canopy. Although high-density combination with wide and narrow rows can increase production, if the canopy is too dense, light cannot reach the bottom, which can easily cause poor development of the lower cotton bolls and a decline in fiber quality. Under conditions of sufficient moisture, uniform row spacing can improve the lighting environment in the middle and lower layers, allowing the cotton bolls to develop better, and both the length and strength of the fibers can be enhanced, making them more mature and consistent. This is because the light distribution is more uniform, providing better development conditions for cotton bolls (Zuo et al., 2024). In addition, some planting methods, such as high-density wide rows, can also reduce leaf residue, accelerate the rate of leaf drop, and are helpful for improving the fiber quality of machine-picked cotton.

4 Interactive Effects of Density and Row Configuration

4.1 Combined effects of planting density and row spacing on plant architecture

Planting density and row spacing interact with each other, thereby altering the structure of cotton plants, including canopy morphology, light distribution and the position of cotton bolls. High-density wide and narrow rows (such as 66 cm+10 cm) can enable the upper canopy to close more quickly, enhance photosynthetic activity, and help increase lint cotton yield, especially in water-scarce environments. On the contrary, moderate density combined with uniform row spacing (such as 76 cm) can make it easier for light to enter the middle and lower parts of the canopy, while increasing the leaf area index (LAI). This is conducive to increasing the biomass of cotton bolls and improving the fiber quality in these areas. During the development stage of cotton bolls, maintaining LAI at around 2.0 can balance the canopy structure and achieve the optimal photosynthetic efficiency.

4.2 Population-level growth balance and mechanisms of yield formation

The planting density and row spacing of cotton will affect the growth state of the entire population, as well as the utilization efficiency of water and nutrients, and thereby influence the yield. If medium density is used, along with uniform row spacing or six-row spacing, cotton can better utilize water and heat. This approach can help accumulate more biomass and also increase the harvest index. Under this configuration, the number and size of cotton bolls can be kept balanced. The water use efficiency (WUE) has been improved, and the output can also be more stable, or even increase. This combination is particularly suitable for arid areas or cotton fields that use drip irrigation. However, if the density is too high or the row spacing is unreasonable, there will be too much competition among the cotton. This will cause the cotton bolls to become smaller, lose weight, have a lower harvest index, and also deteriorate the utilization of water and nutrients (Dong et al., 2025).

4.3 Coupling effects on improving fiber quality

When there is sufficient moisture, using a moderate density with uniform row spacing can significantly improve the fiber quality of cotton, such as making the fibers longer and stronger. This combination works particularly well for the cotton bolls in the middle and lower layers of the canopy. Although high-density planting with wide and narrow rows can increase yield, because cotton is planted too densely, the lower leaves cannot be exposed to sunlight, which can easily lead to poor fiber quality. On the contrary, an appropriate density combined with uniform row spacing not only makes the distribution of cotton bolls more reasonable and ensures more even light exposure, but also enhances the maturity and consistency of the fibers. These studies indicate that as long as the density and row spacing are arranged according to the local water resource conditions, it is possible to achieve both high yield and good fiber quality simultaneously.

5 Regulation by Environmental and Management Factors

5.1 Influence of climatic conditions on the optimization of density and row configuration

Temperature, light and rainfall can affect the suitable density and row spacing of cotton. In places with abundant sunlight and heat, such as Xinjiang, using medium to high density combined with uniform row spacing can enable cotton to make better use of sunlight, improving the efficiency of radiation utilization (RUE) and yield. However, the weather conditions change every year, which can affect the growth and yield stability of cotton. Therefore, the density and row spacing cannot be fixed. They should be appropriately adjusted according to the climate of the current year to reduce the impact of climate change (Xin et al., 2025). In arid or semi-arid areas, high density has certain benefits. Because cotton grows fast, the canopy can close quickly, which can reduce the evaporation of soil moisture and also allow the cotton to mature earlier. However, if the density is too high, it will also cause excessive competition among plants, with leaves blocking each other, which will instead affect their growth. Therefore, the density should be well controlled, neither too high nor too low (Manibharathi et al., 2024).

5.2 Regulatory role of soil fertility and water availability

The amount of nutrients in the soil and the sufficiency of moisture will both affect the planting effect of density and row spacing. If the moisture content is relatively abundant, using medium density with uniform row spacing (for example, 76 cm) will result in better cotton yield and fiber quality, and water will also be used more efficiently (WUE) (Chen et al., 2019; 2022). If there is not enough water, you can choose wide and narrow rows (for example, 66+10 cm) along with a slightly higher density. This combination can better utilize the water in the soil. Even with a small amount of irrigation, the yield can still be stable (Zuo et al., 2023). Apart from water, the fertility of the soil is also very important. High-density planting can help cotton absorb nutrients better and also improve nitrogen utilization efficiency (NUE). However, if the fertilizer is insufficient, the nutrients will be used up quickly, which may instead lead to a deterioration in fiber quality (Wu et al., 2024).

5.3 Compatibility with cropping systems and cultivar types

The setting of density and row spacing also depends on the specific planting method adopted and the variety planted. For instance, in some intercropping systems, such as the combination of cotton and cumin or jujube and cotton, the row spacing and density need to be specially designed to distribute light, water and nutrients more reasonably. Generally speaking, medium density combined with flexible line spacing is more appropriate (Li, 2024; Zhang et al., 2025). In addition, choosing the right variety is also very important. Limited-growth and compact varieties are suitable for high-density planting, which facilitates mechanized operation. For varieties with unlimited growth or vigorous growth, a larger plant spacing should be maintained to prevent excessive growth and facilitate mechanical harvesting (Lakshmanan et al., 2025). Only by integrating these management methods with the local natural conditions can cotton be grown in large quantities and of high quality, achieving sustainable production.

6 Case Studies: Regional Practices in Density and Row Configuration Optimization

6.1 High-yield cultivation practices in the Yellow River cotton-growing region of China

In the Yellow River Basin, when growing cotton, special attention should be paid to the arrangement of density and row spacing, especially when short-season cotton is planted and mechanical harvesting is used. Field experiments have shown that if 112 500 cotton plants are planted per hectare and the wide and narrow row arrangement (66 cm + 10 cm) is adopted, a relatively high and stable seed cotton yield can be achieved, with the maximum reaching 3 832 kilograms per hectare. Under this planting method, the plant height and leaf area index (LAI) of cotton are higher than those under low-density planting. At harvest time, wide and narrow rows can still maintain a better canopy structure and a higher LAI, making the yield more stable. Although the quality of the fibers will not change much, this method is more suitable for mechanical harvesting and is also more conducive to stable production (Li et al., 2023).

6.2 Optimization practices of planting density and row configuration in the southern United States

In the southern United States, the study compared different planting densities and sowing methods, such as hole sowing and row sowing with a row spacing of approximately 96.5 cm. The results show that in hole sowing, high density (up to 152 833 plants per hectare) can increase the lint cotton yield to the maximum (1 465 kilograms per hectare). Only when the density is too low will the output decline. As the density increases, the height of the plants will increase, but other growth and fiber quality indicators change little. If the plants are evenly distributed, reducing the sowing amount can also save costs and will not affect the fiber quality (Siebert et al., 2006). In addition, interlaced planting (such as 2x1 interlaced, with a row spacing of 76 cm) can also maintain yield and income, while reducing costs and having a minimal impact on fiber quality (Larson et al., 2009).

6.3 Studies on narrow row spacing and fiber quality improvement in Central Asia

In these arid regions of Central Asia, research has found that growing cotton in narrow or ultra-narrow rows can increase yields and reduce input costs (Figure 2) (Ye et al., 2021). For instance, by adopting a high-density and narrow row approach, the yield of seed cotton can be significantly increased. Therefore, this method is also recommended to replace the traditional planting model. However, if the density is too high, it may cause the quality of the fibers to deteriorate, such as a decrease in the fineness of the fibers. Therefore, while pursuing output, it is also necessary to pay attention to maintaining fiber quality, and a suitable balance needs to be found between the two. Under this more intensive planting method, the selection of varieties becomes particularly important. Only by choosing the right variety can the output be increased while maintaining the quality of the fiber (Goren and Tan, 2024).

7 Molecular and Physiological Mechanisms

7.1 Effects of density and row configuration regulation on the expression of photosynthesis-related genes

The density and row spacing of planting can affect the photosynthesis of plants and also influence the expression of related genes. If they are planted too densely, the leaves will block each other, and the photosynthesis of the leaves on the vegetative branches will be weakened. In this way, the content of chlorophyll will decrease, and the activity of RuBP carboxylase will also decline, eventually leading to the inhibition of photosynthesis. Some key photosynthetic genes will be downregulated, and the carbohydrates in shaded leaves will also decrease. If the line spacing is arranged reasonably, for instance, by using uniform line spacing and moderate density, the sunlight can be distributed more evenly. In this way, the leaves in the middle and lower layers of the canopy can also maintain an appropriate leaf area index (LAI). This not only enhances the overall photosynthesis (CAP) and radiation utilization efficiency (RUE) of the canopy (Li et al., 2019), but also increases the biomass of cotton bolls, which is beneficial to the quality of fibers.

Figure 2 The field experiment (Adopted from Ye et al., 2021)

7.2 Relationship between optimized population structure and key hormones (IAA, GA, ABA) in fiber development

The group structure formed by density and row spacing can also affect the hormones related to fiber development. Under high density, the plant will increase the auxin (IAA) content and transport efficiency at the main stem tip by upregulating the auxin synthesis gene (GhYUC5) and the transport gene (GhPIN1). Meanwhile, the levels of IAA and cytokinin (CK) in the tips of vegetative branches will decline. In addition, high density also reduces gibberellin (GA) and brassinolide (BR), and upregulates the strigolactone (SL) signal. These changes will inhibit the growth of vegetative branches, making the plant shape more compact. More assimilates are distributed to reproductive organs, reducing cotton bolls from vegetative branches and thereby improving fiber quality (Jan et al., 2022).

7.3 Coordination between root and shoot growth and its role in fiber quality formation

Planting density and row spacing will affect the coordination between the root system and the canopy, which is very important for the efficiency of resource utilization and the quality of fibers. High density combined with appropriate row spacing can make the canopy more compact and the root system more evenly distributed. In this way, plants can absorb water and nutrients better. This combination of roots and leaves also helps maintain photosynthesis. The more stable photosynthesis is, the more nutrients it provides for fiber development, especially when there is sufficient water, this effect will be more obvious. If a balance can be maintained between vegetative growth and reproductive growth, it can ensure the smooth elongation of fibers and the normal formation of cell walls, thus achieving better fiber length and strength (Yao et al., 2017). In addition, cotton itself also has the ability to regulate. It can distribute dry matter to different parts according to environmental conditions and management methods. If the group structure is well designed, this regulatory ability can further enhance the fiber quality.

8 Conclusion

Recent research has found that as long as the density and row spacing are properly arranged, the yield, fiber quality and resource utilization efficiency of cotton in different environments can all be greatly improved. In arid regions, for instance, by using four rows of low-density or six rows of medium-density methods, the utilization rate of water can be enhanced, the distribution of moisture and temperature in the soil can be improved, and the yield will also be higher. In addition, uniform row spacing combined with appropriate density helps optimize the canopy structure and light distribution. This can enable cotton to make better use of sunlight, increase the yield of lint cotton and the quality of fibers. However, many current studies only focus on a single factor, such as density or line spacing, and few studies simultaneously consider the long-term effects under multiple environments and management methods. There are still many challenges in promoting the optimal combination schemes in different regions.

Optimized density and line spacing have potential in many regions. In arid and semi-arid regions such as Xinjiang, China and Central Asia, uniform row spacing combined with moderate density can maintain high yields and stability under water shortage conditions. In intercropping systems such as jujube and cotton, specially designed row spacing arrangements can enhance land utilization, yield and sustainability. In rain-grown or climate-variable areas, flexible row spacing (such as interlaced rows) can reduce risks while maintaining fiber quality. These results indicate that density and row spacing optimization are important means to promote the sustainable intensification of global cotton.

Nowadays, smart agricultural technology also brings new opportunities for the adjustment of density and row spacing. Technologies such as sensor monitoring, data modeling and precision irrigation can flexibly adjust the planting methods according to the actual situation. The Internet of Things (iot) sensors can also monitor soil temperature and humidity in real time, helping growers adjust their plans promptly and use water and fertilizer more economically and efficiently. Future research should take into account more situations where multiple factors act together, such as climate change, soil health, and the interrelationship between genotypes and the environment. With the help of automated and digital tools, precision planting will continue to improve. It can not only increase the yield and quality of cotton, but also reduce input and alleviate the pressure on the environment.

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Conflict of Interest Disclosure

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

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