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Optimizing Planting Density to Enhance Rice Productivity

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Abstract Improving rice yield is of great significance to food security. Under limited arable land conditions, improving yield per unit area by optimizing cultivation measures is a key strategy. Planting density is an important factor affecting rice population growth, yield formation and resource utilization efficiency. This study systematically analyzes the theoretical basis and mechanism of optimizing planting density to improve rice productivity, including the impact on plant growth and development, yield composition, rice quality and economic benefits, and discusses it in combination with practical cases in Nanchang, Jiangxi and Leshan, Sichuan. Studies have shown that a reasonable increase in planting density can increase the number of effective panicles and the number of panicles per unit area, thereby significantly increasing rice yield, but too high density will lead to intensified individual competition, a decrease in the number of panicles, a decrease in the fruiting rate, and an increase in the risk of lodging and disease, which will ultimately be counterproductive. The optimal density varies under different ecological regions and cultivation methods, and should be optimized according to local conditions such as variety characteristics, nitrogen fertilizer management and climatic conditions. The Nanchang Plain double-season rice area has achieved good results by appropriately reducing the sowing density to enhance individual lodging resistance, while the Leshan hilly area has achieved group yield increase through close planting combined with machine transplanting. In general, optimizing planting density requires balancing the relationship between group and individual, source of production and source of storage, to achieve high yield and high efficiency and stable yield and increase income. The comprehensive analysis of this article can provide a scientific basis for high-yield rice cultivation.
Keywords Rice; Planting density; Group growth; Yield composition; Economic benefits; Regional practice

1 Introduction

Rice is the staple food crop for nearly half of the world's population, and improving rice productivity is crucial to ensuring food security. Against the backdrop of limited arable land resources and intensified climate change challenges, how to achieve continuous improvement in rice yield per unit area by optimizing agronomic measures has become a research hotspot and a practical need (Guo et al., 2024). As an important parameter of rice cultivation, planting density (planting density) directly affects population structure and individual development, and plays a key role in the final yield formation. Traditional cultivation often relies on experience to determine density, but there are differences in the optimal density under different varieties and habitat conditions; too sparse planting leads to the failure to fully utilize the production potential of the population, while too dense planting causes individual competition and the risk of lodging and yield reduction. In recent years, with the development of super rice breeding and mechanized cultivation, the theory of achieving high yield through "moderate dense planting" has been proposed. For example, hybrid rice breeding experts in China pointed out that high-yield cultivation not only depends on the genetic potential of the variety, but also requires the coordination of reasonable basic seedlings and population structure (Jiang et al., 2025). Studies have shown that increasing the basic seedling density in combination with single-plant planting is expected to make full use of space resources, promote the construction of large rice populations, and achieve increased yields (Tian et al., 2022). At the same time, the emphasis on density optimization under different ecological conditions is different. For example, double-season rice areas often face the problems of high temperature and high humidity, and plants are prone to excessive growth and lodging. It is necessary to control the basic seedlings to improve the stable yield of the group, while dryland cultivation or direct seeding cultivation often requires increasing the sowing amount to ensure sufficient seedlings to suppress weeds and ensure yield. Therefore, it is necessary to systematically summarize the impact mechanism of planting density optimization on rice productivity and propose strategies adapted to local conditions in combination with regional practices.

This study focuses on the optimization of rice planting density, expounds its theoretical basis, including the theory of population quality formation and the principle of source-sink balance, etc.; analyzes the influence of density on rice growth and development; explores the mechanism of density regulation on yield and composition elements, as well as the impact on rice quality and nitrogen utilization; evaluates the economic benefits of different density treatments; and combines typical practical cases in Nanchang and plain areas of Jiangxi Province and Leshan hilly areas of Sichuan Province to explore the application effects and inspirations of density optimization in different regions. Through literature review and case analysis, this study hopes to provide scientific basis and practical guidance for optimizing planting density to improve rice high yield and efficiency.

2 Physiological Mechanism and Ecological Adaptability of Planting Density Optimization

2.1 Coordination between plant population and individual growth

Rice yield depends on the balanced optimization of group and individual performance, that is, building an ideal group structure to maximize light energy utilization and dry matter accumulation, while ensuring that individual plants have sufficient panicle and fruiting capacity. Planting density directly determines the basic seedling number and the development trend of the group, and is an important regulatory means that affects the three elements of rice yield composition: "number of panicles-number of grains per panicle-grain weight". The theoretical basis of density optimization can be understood from two aspects: group ecology and crop physiology:

2.2 Light interception and canopy ventilation

On the one hand, planting density affects the light interception ability and canopy structure of the group. Under appropriate density, the group can cover the soil surface earlier, increase the leaf area index (LAI), and fully intercept light energy for photosynthesis. Studies have shown that increasing the basic seedling number within a certain range can increase the early LAI and photosynthetic potential of the group, but too high a density will lead to group closure, insufficient light for the lower leaves, and decreased photosynthetic efficiency (Zhang et al., 2021). The experiment of Xie et al. (2016) showed that high basic seedlings and single machine transplanting can form a large group leaf area in the early stage, which promotes the accumulation of total dry matter. However, after exceeding the optimal density, the photosynthetic productivity of the group decreases, and the yield decreases with the increase of density. Therefore, there is a concept of "optimal group leaf area", which makes the utilization of light energy and respiratory consumption of the group reach a balance, so as to maximize the accumulation of net photosynthetic products.

2.3 Impact on root development and nutrient uptake

On the other hand, density affects the growth and development of individual plants and the source-sink relationship. Under sparse planting conditions, there is ample tillering space for individual plants, which can produce more tillers and large panicles, but the number of panicles in the group may be insufficient; under dense planting conditions, the number of tillers per plant decreases, but the number of effective panicles per unit area increases (Zhu et al., 2016; Wei et al., 2021). According to the theory of "compensation effect" of rice, within a certain range, the group yield is stable to density, that is, when the plant density increases, the number of panicles and grains per plant decreases, but the increased number of panicles can often make up for the individual losses, so that the total yield remains unchanged or slightly increases. However, when the density is too high, individual development is severely inhibited, ineffective tillers and spikelet abortion increase within the group, and yield decreases, which is called the "inverted U-shaped" density-yield relationship. For example, Wei et al. (2021) found through a seeding test under drought cultivation that rice yield first increased and then decreased with seeding, reaching a peak at a seeding rate of 195 kg/ha, at which time the number of spikes and the number of grains per mu increased in a coordinated manner. When the density exceeds this, the yield decreases due to poor individual development. This verifies that density optimization requires a balance between group advantages and individual vitality to achieve a match between the source (leaf photosynthetic products) and the sink (grain capacity).

Density also involves the theory of rice population quality. High-yield populations usually require sufficient seedlings in the early stage, reasonable reduction of ineffective tillers in the middle stage, and maintenance of functional leaf activity in the later stage, that is, "enough seedlings in the early stage, stable spikelets in the middle stage, and strong seeds in the later stage" (Huang et al., 2024). If the density is too low, it is difficult to form a sufficient seedling population in time, and if it is too high, the canopy will be closed in the middle stage and prone to premature aging. Chen et al. (2014) pointed out that there is an interaction between planting density and nitrogen application level, which has a significant impact on population dynamics: moderate density combined with medium nitrogen fertilizer level can establish a high-yield population structure with appropriate number of panicles and slow decay of population leaf area. This theoretical basis shows that density optimization often needs to be combined with fertilizer management, and the optimal configuration between panicle number and panicle size can be achieved by cultivating strong seedlings and controlling tillering.

The theoretical basis for optimizing rice planting density is: by adjusting the basic number of seedlings, the population structure is promoted to develop in the direction of having sufficient panicles without damaging individual capabilities, so as to achieve the unity of "maximum productivity of the population" and "optimal function of the individual". This process involves multiple mechanisms such as light energy utilization, growth resource allocation, and source-sink coordination. It is necessary to comprehensively consider variety characteristics and environmental conditions to determine the optimal density range.

3 Analysis of the Impact on Growth and Development

Planting density directly determines the individual growth environment and group ecological conditions of rice, and has a significant impact on the morphological construction, physiological characteristics and growth and development process of the plant. It is mainly reflected in tillering dynamics, plant structure, photosynthetic performance and lodging resistance.

3.1 Tiller dynamics and productive panicles

Density affects tillering occurrence and ear formation rate. Generally speaking, reducing planting density (sparse planting) is conducive to increasing the number of tillers per plant, but too many tillers are often difficult to all ear, resulting in an increase in the proportion of ineffective tillers. On the contrary, increasing density (dense planting) can inhibit the number of tillers per plant, prompting limited tillers to stagnate earlier, thereby increasing the tillering ear formation rate. In the study of Yang et al. (2019), the number of tillers per plant of machine-transplanted late rice was significantly reduced under low nitrogen combined with dense planting treatment, but the total number of ears in the group was equivalent to that of conventional treatment, and the ear formation rate increased by about 5 percentage points, indicating that dense planting helps control ineffective tillers and optimize the group ear structure. Under mechanical transplanting conditions, close planting is often combined with the "one seedling per hole" technology to reduce the number of basic seedlings per pile but increase the number of holes. It is reported that compared with the conventional sparse planting of multiple seedlings per hole, single dense planting can reduce the maximum number of tillers per plant by about 20%, while the number of effective ears is only slightly lower or equivalent, so the ear efficiency (effective tillering rate) is significantly improved. It can be seen that close planting achieves the effect of streamlining individual tillers and improving ear formation efficiency by "controlling tillers with groups".

3.2 Plant height, lodging, and canopy structure

Density changes plant type and canopy structure. Under sparse planting conditions, the plant spacing is large, individual competition is small, and individual plants can form a relatively open plant type and thick stems. When densely planted, the plants tend to be upright and compact, which is manifested by increased plant height, thinner stem base, and narrower and upright leaves. Hu et al. (2023) showed that increasing the planting density significantly reduced the plant height and the length of the internodes below the ear, making the plant morphology more compact, but at the same time the mechanical strength of the stem at the base decreased. Hu et al. (2025) also found that the increase in the density of direct seeding by drones will lead to thinning of the internodes at the base of rice plants and reduction of the thickness of the internode walls. Although it can reduce plant height and the probability of lodging to a certain extent, the ability of stems to resist bending will decrease instead of increase when planted too densely. The spatial arrangement of leaves in densely planted groups is more overlapping, especially the lower leaves are prone to being in a weak light environment. If the density is appropriate, the canopy of the group can present an "ideal plant type" with upright upper leaves and moderately curved middle and lower leaves, which enhances the upper light interception and lower light transmission; when the density is too high, the lower part of the canopy is prone to premature aging and the functional period of leaves is shortened. For example, Wang et al. (2019) compared the canopy characteristics of groups under different plant spacing treatments. The results showed that the leaf area and dry weight of individual plants in the 18 cm plant spacing (moderate density) treatment were significantly higher than those in the 16 cm high density treatment, and the aging rate of functional leaves was slower, indicating that excessive density weakened the development of individual leaf area and functional maintenance. Therefore, density regulation changes the spatial pattern of photosynthetic production of the group by affecting plant type shaping and leaf area distribution.

3.3 Leaf area index (LAI) and photosynthetic efficiency

Density has an important influence on photosynthetic performance and material accumulation. Appropriate dense planting can improve the photosynthetic potential and net productivity of the group. Ling et al. (2024) reported that transplanting strong seedlings cultivated at high density helps to improve the photosynthetic capacity of the group after transplanting. The net photosynthetic rate during the tillering and jointing stages is 2%-5% higher than that of conventional treatments, and the dry matter accumulation is significantly increased. However, excessive dense planting will lead to the obstruction of photosynthetic production in the later stage due to the limited light of the lower leaves and increased respiratory consumption (Figure 1). Liu et al. (2017) found that the group photosynthetic rate of the high density treatment (30 holes/m^2) decreased more than that of the moderate density treatment in the late filling period, which was related to the premature senescence of the lower leaves and the decrease in the light transmittance of the group. On the other hand, the sparsely planted group has many tillers and less nutrient competition, and the individual photosynthetic organs are well developed, and the photosynthetic intensity of a single leaf is usually high, but the total photosynthetic amount of the group may be low due to insufficient leaf area. The results of Wang et al. (2019) showed that under the same nitrogen application level, the 18 cm plant spacing treatment maintained a higher population growth rate and photosynthetic potential during the jointing-heading stage, and the net assimilation rate of the population was more than 5% higher than that of the 16 cm and 20 cm treatments, respectively, thereby accumulating more dry matter. This shows that the photosynthetic efficiency of the population is the highest when the density is moderate. In general, density changes the supply pattern of photosynthetic products by affecting the leaf area and leaf function of the population. In order to give full play to the photosynthetic potential of individuals and populations, a density level should be selected that ensures sufficient photosynthetic area of the population without reducing the light efficiency of a single leaf.

Density also affects rice lodging resistance and the occurrence of diseases and insect pests. In general, sparsely planted plants have strong individuals, thick and hard stems, and strong lodging resistance, but the overall number of panicles in the population is small and the center of gravity is high, which may also lead to lodging (especially when the plants grow excessively when fertilizer and water are sufficient). Dense planting can reduce the center of gravity of individual panicles, but if the stems are thin and weak and the ventilation and light transmission are poor, the population is more prone to wind lodging and disease spread. Li (2020) compared the effects of different sowing densities on the lodging of direct-seeded rice in a double-season early rice experiment in Nanchang. The results showed that appropriately reducing the sowing density (from 25 kg per mu to 15 kg) significantly increased the stem bending resistance and base internode tensile strength of the group, and the lodging rate dropped from 15.3% of the control to 3.8%, proving that excessive density weakens the lodging resistance of the plant. Other studies have pointed out that under high-density planting conditions, the field canopy humidity is high, and the incidence of diseases such as rice blast and sheath blight often increases. Therefore, when optimizing density, both plant stress resistance and field hygiene conditions must be taken into account. It is generally recommended to moderately reduce the basic seedling density or use wide and narrow rows to improve ventilation and light transmission in an environment prone to lodging and disease, so as to improve the robustness of the group.

Planting density affects rice tillering dynamics, plant height and plant type, leaf area index, and stem strength, thereby shaping different group growth characteristics. Appropriate density can promote the balanced growth of rice populations and enhance the photosynthetic performance and stress resistance of the population; too dense or too sparse will break this balance. The former will lead to internal consumption of the population and inhibited individual development, while the latter will cause waste of resources and insufficient population effect. Therefore, in cultivation practice, the tillering and plant type characteristics should be dynamically monitored during the growth period, and density-related measures (such as thinning and replanting) should be adjusted in a timely manner to form an ideal population growth and development situation and lay the foundation for high yield.

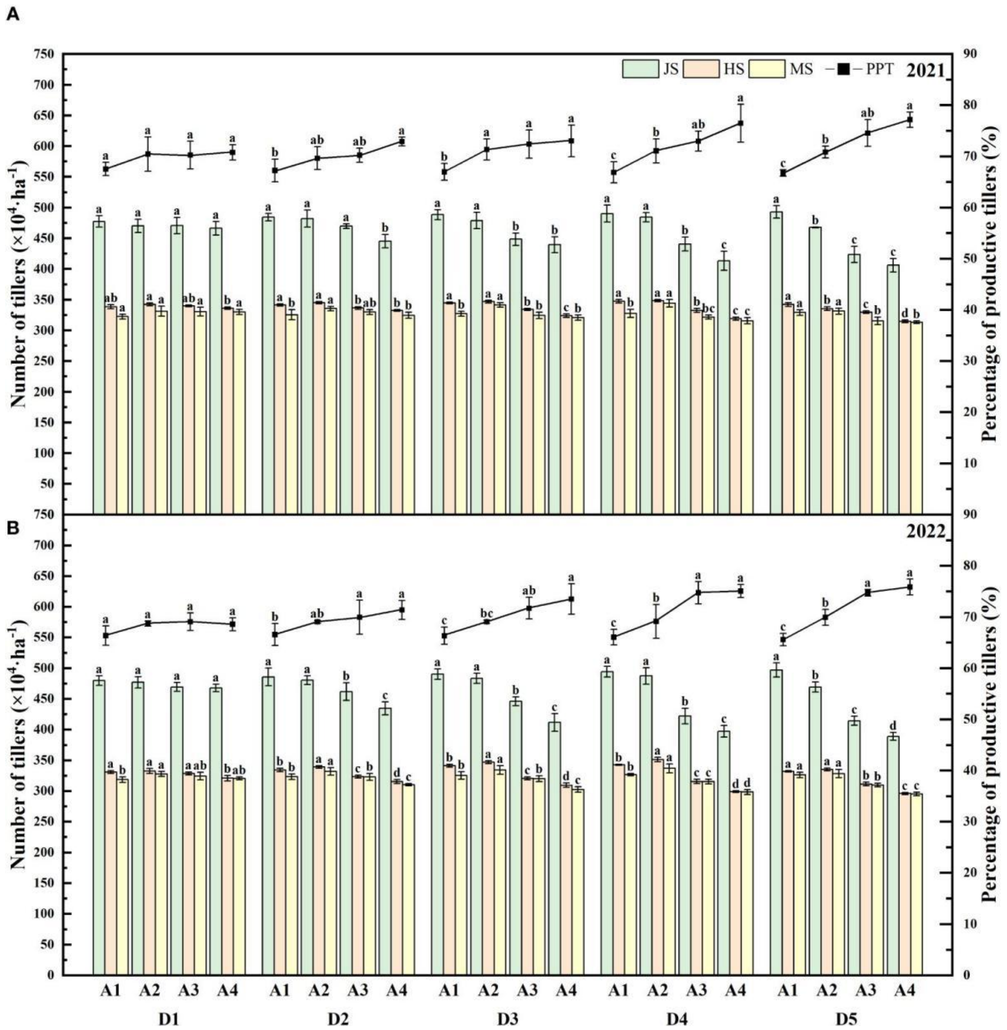

Figure 1 Tillers and percentage of productive tillers of rice affected by increased seeding density and seedling age with crop straw boards for seedling cultivation. (A) Tillers and percentage of productive tillers of rice in 2021. (B) Tillers and percentage of productive tillers of rice in 2022 (Adopted from Ling et al., 2024)

4 Impact on Yield and Its Components

The level of rice yield depends on three main components: the number of effective panicles, the number of grains per panicle and the thousand-grain weight. Changes in planting density will have a significant effect on the final yield by affecting the above factors. Density will also affect rice quality and nutrient utilization efficiency.

4.1 Changes in panicles, grain number, and 1 000-grain weight

Planting density determines the number of effective panicles per unit area and is the primary factor affecting yield. Generally speaking, increasing density can significantly increase the number of effective panicles, while reducing the number of grains per panicle and the fruiting rate; conversely, reducing density increases the number of grains per panicle and grain weight, but reduces the number of panicles. This trade-off effect determines that the yield-density relationship is a quadratic curve of "first increase and then decrease". Many experiments have verified that the optimal density corresponds to the peak yield: Zhu et al. (2023) reported that the yield of drone-sown rice was the highest when the basic seedlings were 1.95 million plants/hectare, an increase of about 6% from 1.5 million plants/hectare, while the yield decreased when it continued to increase to 2.4 million plants/hectare. Hu et al. (2025) also found in the drone direct seeding experiment that both types of rice varieties achieved the highest yield at the intermediate density (about 30 plants/m^2 for conventional japonica rice and about 12 plants/m^2 for two-line hybrid rice), and their yield increased by 4%-6% compared with the low density and 6%-8% higher than the highest density. These results show that the combination of various elements of yield composition can be optimized by adjusting the density to maximize the yield.

Specifically, density mainly affects the yield composition through the following channels:

Effective panicle number: Increasing density usually linearly increases the number of effective panicles per unit area, which is one of the main contributing factors to the increase in yield by dense planting. Under mechanical transplanting conditions, when the basic seedling density was increased from 16 holes/m^2 to 20 holes/m^2, the number of ears increased by 8%-12%, and the yield increased accordingly (Hou et al., 2019). The high-density treatment produced 2-3 more ears per square meter than the conventional density, and the yield increased by about 5% (Tang et al., 2020). However, when the density is too high, the ability of some tillers to form panicles decreases, and even "spikelets" or deformed panicles appear in the population, resulting in the number of effective panicles no longer increasing or even decreasing with increasing density. Therefore, there is a critical density that makes the number of effective panicles reach the maximum value.

Number of grains per panicle: dense planting tends to reduce the number of grains per panicle, including the number of spikelets and the number of fruiting grains per panicle on primary and secondary branches. Hu et al. (2025) observed that the total number of grains per panicle decreased from low to high density. For example, when the density of ordinary japonica rice was reduced from 15 plants/m^2 to 30 plants/m^2, the number of grains per panicle decreased from about 185 to 163, a decrease of about 12%. The two-line hybrid rice also decreased by a similar amount. This is because the vegetative growth in high-density populations is inhibited and the panicle type of individual plants becomes smaller. At the same time, the excessively high density leads to insufficient light in the panicle area, and the limited development of floral organs will also reduce the number of spikelets per panicle. In contrast, sparse planting can form large panicles because the individual plants have sufficient nutrition, and the number of branches per panicle, especially the secondary branches, increases. For example, Huang et al. (2018) found that the average number of spikelets per ear in the treatment of multi-seedling traditional machine transplanting (relatively low density) was about 15 more than that in the treatment of single-seedling high-density machine transplanting. However, the decrease in the number of grains per ear is often offset or even exceeded by the increase in the number of ears, so the total number of spikelets (the total number of grains per ear per square meter) still increases within a certain range of density. For example, when compared under low nitrogen treatment, the total spikelet number in the densely planted population was still 4.5% higher than that in the sparsely planted population, although the number of grains per ear was reduced (Yang et al., 2019).

Grain setting rate and grain weight: Due to fierce resource competition in high-density groups, grain filling may be affected, which is manifested as a decrease in grain setting rate and a slight decrease in thousand-grain weight. Chen et al. (2023) showed that increasing planting density would lead to a decrease in rice grain setting rate by 0.5-1.5 percentage points, but had little effect on thousand-grain weight. Yang et al. (2019) also reported that the fruit set rate of the dense planting treatment was slightly lower than that of the conventional treatment by about 2 percentage points, mainly because the small flowers at the bottom of the panicle were easily empty and barren due to light and nutrient restrictions. The sparse planting group has a stronger assimilation capacity per plant, and the fruit set is sufficient, and the thousand-grain weight is often slightly higher. But in general, compared with the changes in the number of panicles and the number of grains, the density has a smaller effect on the fruit set rate and grain weight. In actual production, the thousand-grain weight is more determined by the genetics of the variety, and it is difficult to significantly change the grain weight by adjusting the density. Therefore, the change in yield with density is mainly reflected by the increase and decrease of the number of panicles and the number of grains per panicle.

There is an obvious trade-off relationship between planting density and the three elements that constitute rice yield. Density increases → number of panicles increases → number of grains per panicle decreases → yield presents an inverted U-shaped curve. In order to obtain the highest yield, it is necessary to choose a balance point so that the product of the number of panicles and the number of grains per panicle is maximized and the fruit set rate is guaranteed. A large number of studies and production practices have shown that this equilibrium density usually corresponds to the suitable range of basic seedlings under different cultivation modes: for example, ordinary hybrid rice cultivated by transplanting is 16-20 holes/m^2, japonica rice is 20-30 plants/m^2, and direct-seeded rice is about 1-1.5 million seedlings/hectare (equivalent to 15-22.5 plants/m^2). Beyond this range, some aspects of the group or individual will become limiting factors. For example, Jiang et al. (2021) pointed out in their study on hybrid rice under high temperature and high humidity that reducing nitrogen fertilizer combined with moderately dense planting (basic seedlings are about 30 plants/m^2) can improve the coordination of panicle-grain structure, thereby increasing both yield and nitrogen fertilizer utilization efficiency. On the contrary, blindly dense planting at the same nitrogen level will significantly reduce the fruit set rate and grain weight, although the number of panicles will increase, and the final yield will decrease instead of increase.

4.2 Nonlinear yield-density relationships

In addition to yield, planting density also affects indicators such as rice quality and fertilizer utilization efficiency. Generally speaking, dense planting will reduce the rice quality to a certain extent. The main reason is that the supply of assimilates in the later stage of the dense planting population is relatively insufficient, resulting in poor grain enrichment, decreased grain weight and increased chalkyness. Chen et al. (2023) found that high-density treatment reduces the appearance quality of rice and the cooking flavor quality, such as the rice rate and amylose content, both of which have decreased. Hu et al. (2017) also reported that increasing density under machine insertion conditions reduced the gel consistency and protein content of the grains, and the rice quality slightly worsened. This reminds you to pay attention to quality changes while pursuing output. It is worth noting that density affects quality often interacts with fertilization level: high-density populations are prone to produce more serious problems of chalky rice and excessive protein under high nitrogen conditions, while moderate reduction of nitrogen fertilizers combined with dense planting can partially alleviate the decline in quality. Therefore, in high-yield cultivation, it is often achieved by optimizing the fertilizer and density combination to achieve "both high-yield and high-quality".

In terms of nutrient utilization, appropriate density increases are usually beneficial to improving nitrogen fertilizer utilization efficiency (NUE). Close transplantation can increase the total amount of nitrogen absorption in the population and increase nitrogen absorption per unit area. Hou et al. (2019) showed that under mechanical transplantation conditions, the partial productivity of nitrogen fertilizers and nitrogen recovery rate were significantly improved under higher density (25% increase in basic seedlings per hole) treatment. Jiang et al. (2021) also pointed out that tight planting and nitrogen reduction can achieve high yield and high efficiency by "smashing nitrogen supplementation": in the southern double-season rice area, the yield of nitrogen fertilizer reduced by 15% under high temperature and high humidity conditions and increased by 20% of basic seedlings is the same as usual, but the nitrogen fertilizer utilization rate has increased by more than 8%. It can be seen that density optimization is one of the important measures to achieve efficient fertilizer saving. In addition, density affects the mass water transpiration and soil nutrient consumption rhythm, thus related to the efficiency of water and fertilizer utilization. Generally, dense planting groups consume water and fertilizer faster in the early stage, and resource utilization is relatively sufficient in the middle and late stages, but excessive density may cause fertilizer waste due to early aging in the later stage. Therefore, reasonable water and fertilizer management and density adjustment are required to be optimized simultaneously.

4.3 Influence on yield stability across seasons

The optimal density will vary in different ecological regions and varieties. For example, in the northern single-season rice areas with sufficient light temperature, individual production potential is great, and lower density is often used to give full play to the advantages of large ears. In the southern double-season rice areas, the density is relatively high due to the short growth period and the emphasis on population ears. Jiang et al. (2017) found in the experiments of the middle and lower reaches of the Yangtze River that compared with plain areas, dense planting in hilly areas (poor ecological conditions) has a more obvious effect on the increase in yield, and a higher basic seedling is needed to ensure sufficient ear count. On the contrary, in areas with high soil fertility and sufficient light, slightly thinning is conducive to cultivating large ears and achieving the combination of "large ears and many ears". In terms of variety, conventional rice or japonica rice with strong tillering ability can generally have a lower density to allow them to fully tiller; hybrid indica rice with weak tillering ability needs to rely on higher basic seedlings to make up for the ear number. For example, the optimal basic seedling density for conventional japonica rice is about 30 plants/m^2, while the maximum yield for hybrid two-line rice is about 12 plants/m^2 (Hu et al., 2025). This reflects the importance of adjusting density according to variety characteristics.

At the yield and constituent factors, the optimization of planting density mainly revolves around the balance between increasing the number of ears and maintaining appropriate ear types. A large number of experimental data support the law of "medium density and high yield", that is, extreme sparse planting or extreme dense planting is not conducive to the maximum output. In practice, a reasonable basic seedling range should be determined based on local ecological conditions and variety characteristics. On this basis, fertilizer and water management are supplemented to achieve the best matching of group production and resource utilization, and obtain high yields, stable yields and good rice quality. Both research and practical experience show that optimizing planting density is a simple and efficient high-yield cultivation method, which is of great significance to improving quality and efficiency of modern rice production.

5 Economic Benefit Evaluation

In the optimization of agronomic measures, we should not only pay attention to the increase in yield itself, but also evaluate the changes in input-output and economic benefits. The impact of optimizing planting density on the economic benefits of rice production is mainly reflected through the combined effects of yield benefits, seed costs, fertilizer and pesticide inputs, and risk factors.

5.1 Net return per hectare

From the perspective of yield benefits, the above analysis shows that reasonable dense planting can increase yield per unit area, thereby directly increasing grain output benefits. When other inputs remain unchanged, yield increase means increased sales revenue. For example, Tang et al. (2020) reported that the per mu yield of high-quality late rice increased by about 5% under density optimization treatment. According to the market rice price, the increase in income per mu was about 100 yuan (assuming rice is 2.5 yuan/kg), showing positive economic benefits. However, it is necessary to consider that excessive density may lead to a decline in rice quality or a decrease in the selling price. If the rice quality declines significantly, it may partially offset the benefits brought by the increase in yield. Therefore, in the production of high-quality rice, density adjustment should take into account both yield and quality to ensure an increase in total benefits.

5.2 Cost-benefit comparison under different densities

Seed and cultivation costs change with density. Increasing the planting density usually means an increase in the amount of sowing or the number of seedlings, and an increase in seed costs. However, in areas with a high degree of mechanization, the proportion of seed costs in the total cost is not large. For example, if the sowing amount per mu increases by 1 kg, the cost will only increase by about 20 yuan, which is still a cost-effective investment compared with the increase in yield. It should be noted that in the case of direct seeding or seedling throwing, excessive sowing will significantly increase seed costs and labor costs, which may not be economically cost-effective. Therefore, the balance point of increased yield vs. increased costs should be calculated. Li (2020) compared the economic benefits of different sowing amounts for double-season direct seeding rice: the results showed that the yield and income of the medium sowing amount (15 kg per mu) were higher than those of the low sowing amount, and only 0.2 kg of seeds were required for each additional kg of rice, and the input-output ratio was relatively high; while the excessive sowing amount (25 kg) slightly increased the yield, but the increase in seed input exceeded the output value gain, and the net income decreased. It can be seen that there is an optimal density that maximizes the marginal output per unit input.

5.3 Optimal economic density range

Density optimization affects the efficiency of fertilizer and plant protection inputs. Reasonable close planting can often improve fertilizer utilization, which may reduce the demand for fertilizer and thus save costs. The experiment of Wang et al. (2018) showed that when the sowing rate of 195 kg/ha was combined with 140 kg/ha of nitrogen, the same high yield was achieved with a reduction of about 18% in nitrogen fertilizer use, and the fertilizer cost was reduced compared with the traditional nitrogen application of 170 kg/ha + low sowing rate. This is beneficial to economic benefits. In addition, the weed suppression effect of densely planted fields is better, which can reduce the cost of weed control; but excessively dense planting leads to aggravated diseases, which will increase pesticide input and even cause production losses, thus negatively affecting the benefits. Therefore, it is necessary to consider the changes in input comprehensively. Only by combining moderately dense planting with scientific fertilizer and pesticide management can we achieve "increased production without increased cost" or "increased production with slightly increased cost and greater increase in benefits".

Risk factors such as the risk of lodging and reduced yield are also related to density, which affects economic benefits. Lodging will seriously affect the yield and harvest quality, causing direct economic losses to farmers. Too high density often increases the probability of lodging, bringing potential risk costs. Correspondingly, slightly reducing the density can improve the resistance of the group to lodging and reduce the probability of yield reduction due to lodging, which is equivalent to a risk-averse benefit. Jiang et al. (2021) showed that in hot and rainy areas, the implementation of nitrogen reduction and dense planting technology increased the density, but by simultaneously reducing the growth potential of nitrogen fertilizer, the stalk strength was maintained, lodging did not occur, and the income was stable. This suggests that reasonable density can reduce the probability of disaster losses to a certain extent and have a positive effect on long-term average income. In addition, appropriate density can also reduce ear loss and mechanical damage during the harvesting process, and increase the yield of commercial rice, which is also one of the economic benefit factors.

A brief economic analysis is conducted using the double-season rice in Nanchang, Jiangxi as an example: under the control density (traditional) conditions, the yield of early rice per mu is about 500 kg, the rice income is 1 250 yuan, the seed cost is 40 yuan, and the net income is 1 210 yuan; by optimizing the sowing density and the basic seedlings of the rice seedlings, the yield per mu is increased to 530 kg, the income is 1 325 yuan, the seed cost is 50 yuan, and the lodging loss is reduced by about 30 yuan, which is included in the income. The net income is about 1 305 yuan, which is 95 yuan more than the control, an increase of 7.9%. It can be seen that density optimization has achieved a considerable increase in net income while maintaining or slightly increasing the cost. This benefit is of great economic significance when planted on a large scale. Looking at the hybrid rice in the hilly area of Leshan, Sichuan, due to the use of single-plant dense planting machine transplanting technology, the seedling cost is slightly higher than the conventional one, but the yield per mu is increased from 600 kg to 650 kg, and some weeding costs are saved at the same time. The overall income per mu increased by nearly 150 yuan, showing a good rate of return of "high input brings higher output".

It should be emphasized that the economic benefit evaluation should take into account the cost structure and goals of different entities (farmers/cooperatives). If only the highest yield is pursued without considering the cost, the phenomenon of high yield and low benefit may occur; on the contrary, excessive cost saving may miss the opportunity to increase production. Therefore, the unit cost benefit or benefit-cost ratio should be used as the evaluation indicator. In existing studies, Zhang et al. (2023) found through drone dense planting experiments that when the density increased from 150 to 300 g/tray, the rice output per kilogram of seeds gradually decreased, and the benefit-cost ratio reached the highest at 250 g/tray, and the ratio decreased when the density increased further. This type of analysis helps to find the density with the best economy rather than only the best yield.

Optimizing planting density can usually improve the economic benefits of rice production, but it is necessary to balance the relationship between increased yield benefits and increased input. The yield benefits brought by moderately increasing density are often greater than the increase in seeds and other costs, and can also improve resource utilization efficiency and reduce certain risk costs, thereby increasing net profit. However, density beyond a reasonable range will cause diminishing returns or even reduce net income. Therefore, when promoting the technology of dense planting and yield increase, we should emphasize supporting cultivation and economic accounting to ensure that farmers can "increase their input by a little and get double the output" and achieve real high yield and high efficiency. For example, conducting typical surveys of rice farming systems in different regions and optimizing planting density parameters with the goal of maximizing economic benefits will be conducive to the sustainable adoption of technology and increasing income and efficiency of food production.

6 Case Study: Practical Enlightenment of Regional Application

In order to better apply the above theories and influencing laws to production practice, the following takes the plain rice area in Nanchang, Jiangxi and the hilly rice area in Leshan, Sichuan as examples to explore the implementation effect and experience enlightenment of planting density optimization under different ecological conditions.

6.1 Density and lodging resistance practice in the double-season rice area in Nanchang, Jiangxi

Nanchang is located in the central plain of Jiangxi, with a warm and humid climate and a long history of double-season rice planting. The early rice in this area is heading and filling in the plum rain season, and often encounters high temperature, high humidity and rainy weather. Plant leggy growth and lodging are one of the main problems that limit yield. Traditionally, local farmers often increase the basic seedlings in order to achieve high yields. The hand-planting density of early rice is generally above 20 holes/m^2, with 2-3 plants per hole. However, this method is prone to lead to group closure, elongation of the base internodes, and large-scale lodging in the event of strong winds and rainstorms, which seriously affects yield and harvest. In recent years, Jiangxi Agricultural University and local agricultural technology departments have cooperated to carry out double-season rice density optimization cultivation experiments to promote the technology of "appropriately reducing density and cultivating strong seedlings". Taking Li (2020)'s research experiment as an example, in the early rice fields in the suburbs of Nanchang, three seeding rates of 12.5 kg, 15 kg and 25 kg per mu were set, which was equivalent to a basic seedling density of about 800 000, 1 million and 1.7 million seedlings per hectare. The results showed that the population of the medium seeding rate (15 kg/mu) treatment grew neatly and robustly, with 320 effective ears per square meter, which was slightly lower than the high seeding rate treatment by 5%, but the number of grains per ear was 8% higher, the fruiting rate increased by 2 percentage points, and there was no significant difference in the final yield. More importantly, the high seeding rate treatment suffered from varying degrees of lodging in both years of the experiment, with a lodging rate of 15%-20% during the fruiting period, while the medium seeding rate treatment had basically no lodging. Although the low seeding rate treatment had thicker stems, the number of ears was less and the yield was slightly reduced. In terms of comprehensive benefits, the medium seeding rate (moderately reduced density) treatment achieved the highest benefits. Therefore, researchers recommend that the sowing rate of Nanchang double-season early rice direct seeding should be about 15 kg per mu, supplemented by soil testing and formula fertilization and growth regulator control, which can effectively balance the number of ears and ear weight, reduce the risk of lodging, and achieve stable and increased yields. This practical case shows that in areas with high lodging risk, reducing the planting density to enhance individual resistance to lodging and improve group robustness is a practical and effective way. After the promotion of this technology in Nanchang, the average lodging rate of early rice in multiple demonstration fields has dropped from more than 10% in the past to less than 3%, with a reduction of about 40 kg per mu, equivalent to reducing losses and increasing profits by about 100 yuan (Liao et al., 2023). Farmers reported that the density optimization technology is simple and easy to use, does not require additional equipment investment, and is easy to accept. At present, the planting density of early rice in this area has shown a significant downward trend compared with ten years ago, and the group quality and yield stability have been significantly improved. This shows that density management has played an important role in updating cultivation concepts and improving risk resistance in traditional rice areas.

6.2 Application of dense planting and machine transplanting in the hilly area of Leshan, Sichuan

Leshan City is located on the southwestern edge of the Sichuan Basin. It is dominated by hills and plains. There are many scattered rice fields and the degree of mechanization started late. The rice cultivation in this area is mainly medium-season rice or one-season late rice, and most of the varieties are hybrid indica rice. In the past, due to the long seedling age of the seedling field and the low transplanting density (generally about 16 holes/m^2, 4-5 plants per hole), the number of panicles in the group was insufficient and the high-yield potential was not fully utilized. According to a survey by the local Academy of Agricultural Sciences, before 2015, the average number of panicles per mu of rice in Leshan was only about 1.6 million, and the yield per unit area hovered around 500 kg for a long time. The experience of Hunan and other places shows that the machine transplanting cultivation technology of "one hole, one seedling, dense planting and shallow transplanting" can significantly increase the yield of super rice. To this end, the Leshan Agricultural Technology Extension Center has introduced and promoted the dense planting and machine transplanting technology since 2018, and verified its yield-increasing effect by building demonstration plots. Taking the demonstration in Wutongqiao District in 2019 as an example, the widely adaptable hybrid rice variety "Yixiangyou 2115" was selected to compare the differences between traditional manual planting (15 holes/m^2×4 books per hole) and dense planting machine planting (30 holes/m^2×1 book per hole). Under the same fertilizer and water management, the number of effective ears per mu in the dense planting machine planting treatment reached about 2.2 million ears, 400 000 more than the control; although the total number of grains per ear dropped from 150 grains in the control to about 130 grains in the dense planting treatment, the fruit set rate of the two was similar and there was no difference in thousand-grain weight. In the end, the dense planting machine planting treatment had an acreage yield of 837 kg, while the control was 745 kg, an increase of 12.3%. At the same time, the plant height of the dense planting machine planting group was slightly lower, the coarseness and hardness of the stems were comparable to the control, no lodging occurred, and the appearance quality of rice, such as the rate of whole polished rice, was not significantly different from the control. Xie et al. (2016) concluded that the key to the success of dense planting and single machine transplanting in the hilly areas of southwest China such as Leshan is: first, mechanized seedling cultivation ensures the quality of seedlings and the implementation of small seedling machine transplanting; second, the matching of wide and narrow row planting mode (such as alternating 30 cm wide row spacing + 13 cm narrow row spacing) improves the ventilation and light conditions of dense planting groups. After three consecutive years of practice in the Leshan demonstration area, the average per mu yield of dense planting and machine transplanting rice increased by 8%-15% compared with the traditional method. At the same time, 0.5 kg-1 kg of seeds were saved per mu, and there was basically no need to supplement seedlings, which greatly reduced labor and achieved significant overall benefits. At present, this technology has been promoted to tens of thousands of mu in Leshan City, becoming a new highlight of local grain production increase. The inspiration we can get from the Leshan case is that in hybrid rice areas with medium soil fertility and average tillering ability, by increasing the planting density and adopting single seedling transplanting, the potential of large panicles of hybrid rice can be fully utilized while significantly increasing the number of panicles and achieving a breakthrough in high yield. At the same time, with a reasonable planting layout, the negative effects of dense planting can be avoided. This has a strong reference significance for similar areas such as Sichuan hills. During the promotion process, we should focus on solving the technical bottlenecks of mechanical transplanting (such as the strength of the seedling board and the flatness of the field), and adjust the row spacing and basic number of seedlings according to local conditions. For example, the field test in Leshan Pingba showed that the yield of the 30 cm×12 cm configuration (one seedling per hole) was better than that of the 25 cm×16 cm configuration, indicating that appropriately increasing the row spacing and increasing the hole density are more conducive to increasing yield. These practical details and experiences enrich the application methods of density optimization and provide a reference for promoting high-yield technology of dense planting under different terrain conditions.

6.3 Comparative analysis and key takeaways

The two cases of Nanchang and plain rice areas and Leshan hilly rice areas represent two different ecological types, and the needs and strategies for density optimization are different: the former focuses on reducing density to prevent lodging, stabilize yield and improve quality, while the latter focuses on increasing density to tap potential, increase yield and increase efficiency. But the common point between the two is that they have achieved substantial results by adjusting the basic seedlings and planting methods, proving that density optimization plays an important role in different environments. At the same time, the case also reflects that density management needs to be combined with other agronomic measures. For example, in the Nanchang case, if the control measures are not taken, simply reducing the density may reduce the yield, so the density was reduced and ear fertilizer was applied appropriately early to make up for the number of grains per ear; in the Leshan case, if there is no mechanical single-planting and wide and narrow row support, simply increasing the density is also difficult to work. This reminds us that the optimization of planting density should be considered as a part of the integrated high-yield cultivation technology system, and it should be considered in conjunction with variety selection, seedling raising methods, fertilizer and water management, etc., in order to achieve the best results in practice.

For plain areas, attention should be paid to the impact of density on the stable yield of the group, and moderately dense planting but not over-dense should be used to ensure strong plant type and resistance to lodging; for hilly areas and areas with low yields, dense planting technology should be used to improve group productivity, but it is necessary to prevent over-dense planting from causing insufficient resources (Lei et al., 2025). In practical promotion, demonstration experiments should be strengthened and density optimization paradigms should be formulated according to regional characteristics. For example, basic rice seedling indicators and operating procedures for different production areas should be formulated for farmers to refer to and implement. At the same time, the success of the case also shows that density optimization is a measure with low investment and quick results. It is very suitable for promotion and application in large rice-growing areas, providing support for increasing rice production and farmers' income.

7 Concluding Remarks

Reasonable dense planting is one of the key measures to achieve high rice yields. By moderately increasing the planting density, the number of effective panicles and total spikelets per unit area can be increased, thereby significantly increasing yield. However, there is a critical value in the relationship between density and yield. If the density is too high, the yield will decrease due to the inhibition of single plant development, the number of grains per panicle, and the decrease in fruiting rate. Therefore, it is necessary to determine the optimal density range under variety and environmental conditions to achieve the best balance between panicle number and panicle type.

Density optimization requires a comprehensive consideration of the coordinated development of the group and the individual. Appropriate density helps to build a group structure with high photosynthetic efficiency and healthy and robust individuals. Under dense planting conditions, the utilization of light energy and dry matter accumulation of the group increase, but individual competition is also more intense; sparse planting is the opposite. The essence of optimizing density is to maximize the production capacity of the group without significantly weakening the panicle formation and filling capacity of the individual plant. To achieve this, it is also necessary to combine it with fertilizer and water management, and coordinate the source-sink relationship and the reproductive process.

The optimal planting density varies in different ecological regions and variety types, and needs to be adjusted according to local conditions. In areas with high temperature and rainfall and high risk of lodging, it is advisable to appropriately reduce the density to enhance lodging resistance and stable yield; in areas with sufficient light and heat resources and weak tillering ability, the density can be increased to increase the potential number of panicles. Japonica rice, conventional rice, etc. can use lower basic seedlings, while hybrid indica rice usually requires higher basic seedlings. Regional trials and demonstrations are crucial to exploring the optimal density parameters in various places.

Optimizing planting density can generally improve resource utilization efficiency and bring better economic benefits while increasing yield. Moderately dense planting usually increases nitrogen fertilizer utilization and enhances weed suppression, thereby reducing the input cost per kilogram of rice. Empirical cases show that while increasing yield through density management, farmers' net income also increases simultaneously. However, we should guard against the risk of rice quality decline and disease caused by excessive dense planting to avoid affecting quality benefits.

In practice, the optimization of planting density needs to be integrated with cultivation technology. Measures such as single-plant dense planting by machine, wide and narrow row spacing configuration, and fertilizer and water regulation during the tillering period can effectively alleviate the negative impact of density changes and amplify the yield-increasing effect of density optimization. When promoting dense planting and high-yield technology, different regions should provide a complete technical solution, including improvement of seedling raising methods, integration of agricultural machinery and agronomy, etc., to ensure the realization of the expected effect.

Optimizing planting density is a core strategy for high-yield rice cultivation. Its principle is simple and clear, and the operation is relatively easy. It has been proven to have the potential to increase yield in all kinds of rice farming ecology. Looking to the future, more attention should be paid to refined group management in rice production, and planting density should be used as a precise cultivation parameter for scientific design and dynamic regulation. At the same time, strengthen the research on related mechanisms and intelligent monitoring to provide a basis for density decision-making in different situations. Through research and promotion, fully tapping the production potential of rice groups and achieving the unity of high yield, high quality and high efficiency is an important way to ensure food security and sustainable agricultural development.

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