

Feature Review

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Effect of Wheat Sowing Density on Seedling Growth and Final Yield

Pingping Yang, Xuemei Liu ✉

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

✉ Corresponding email: xuemei.liu@hitar.orgField Crop, 2025, Vol.8, No.5 doi: [10.5376/fc.2025.08.0025](https://doi.org/10.5376/fc.2025.08.0025)

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Abstract Wheat (*Triticum aestivum*) is one of the most important global staple crops, and optimizing its cultivation practices is essential for ensuring food security and economic efficiency. This study investigates how varying sowing densities influence early seedling development and ultimate yield outcomes in wheat. We examined the biological basis of density effects, including intra-species competition, resource allocation, and hormonal signaling, and evaluated how these factors shape early seedling vigor, tillering capacity, and root expansion. We also assessed how sowing density impacts final yield components, such as spike number, grain weight, and biomass accumulation, in interaction with environmental and management variables like soil fertility, climate, and agronomic practices. A regional case study further highlights practical outcomes of density variation. Finally, we explored advances in precision agriculture technologies-including remote sensing, AI modeling, and variable-rate seeding-for optimizing sowing density. This study concludes that fine-tuning sowing density based on local conditions and technological tools can significantly enhance wheat productivity and sustainability, while also identifying key knowledge gaps requiring further research.

Keywords Wheat (*Triticum aestivum*); Sowing density; Seedling growth; Final yield; Precision agriculture

1 Introduction

Wheat is one of the most common staple foods in the world. It provides the main source of calories and protein for many people. Because wheat can adapt to various climates and soils, it has become an important support for global agriculture and food security. Under environmental changes and economic pressures, people have been working hard to improve wheat yield and stress resistance (Chaplygin et al., 2023; Zhang et al., 2023).

Seeding density is a very important factor when growing wheat. It affects the growth of seedlings, the appearance of leaf cover, the efficiency of sunlight and nutrient use, and ultimately affects yield and quality. If the density is appropriate, it will not only make the crop grow better, but also improve the microclimate in the field, while reducing seed and management costs while increasing yield (Abati et al., 2018; Chen et al., 2022). However, if the density is not appropriate, it may cause poor seedling emergence, waste of seeds, or reduced yield, which means that we need to accurately adjust the seeding density according to local conditions and varieties (Spink et al., 2000; Marinho et al., 2022).

The goal of this study is to summarize the current research results on the effect of seeding density on wheat growth and yield. We will analyze the relationship between different densities and seed vitality, sowing date, variety characteristics, and environmental conditions to see how they affect seedling growth, canopy structure, and yield composition. By collecting data from field experiments and indoor trials, we hope to provide some practical suggestions for optimizing wheat sowing density to help farmers increase yields and obtain better economic benefits.

2 Biological Basis of Sowing Density Effects

2.1 Impact of plant competition on root and shoot development

When wheat is planted too densely, the plants compete for sunlight, water, and nutrients. This competition can make each plant smaller, with fewer tillers and branches and fewer roots. Modern varieties that pursue high yields and are not very competitive are particularly susceptible (Zhu et al., 2022). When planted at high density, the roots of the aboveground part will develop poorly, and the ratio of roots to stems will also change. Compared with traditional old varieties, modern wheat varieties use more energy on reproductive structures such as ear formation,

and less on the root system (Rehling et al., 2021). In addition, wheat can "sense" the root density and soil space around it, and then adjust its growth pattern (Figure 1). In this way, they can better adapt to crowded environments and avoid insufficient resources (Wheeldon et al., 2021).

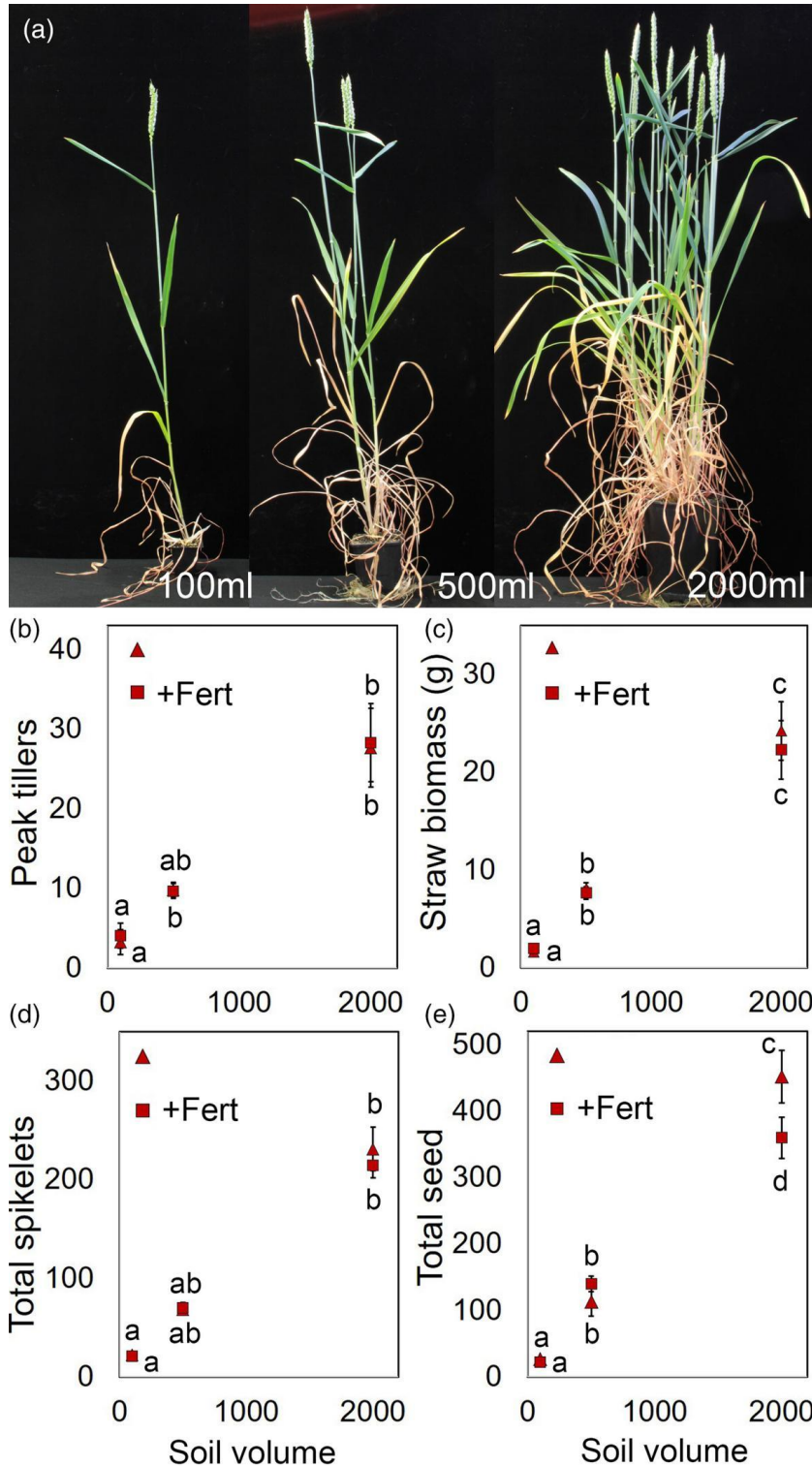


Figure 1 Soil volume directly influences plant growth independently of nutrient levels. (a) Final plant size in spring wheat plants grown in 100, 500 and 2000 ml of soil (photos are to scale). (b-e) Graphs showing the relationship between soil volume and mean peak tiller number (b), straw biomass (c), mean total spikelets (d) and mean total seed (e) in spring wheat (Mulika) in 100, 500 and 2000 ml of soil, without supplemental fertilizer (closed triangles) or with additional fertilizer ('Fert') (closed squares). Error bars indicate SEM, $n = 6-12$. Data points with the same letter are not statistically different from each other; Kruskal-Wallis (c) or analysis of variance + Tukey HSD (c-e) (Adopted from Wheeldon et al., 2021)

2.2 Influence of light interception and photosynthetic efficiency

If you plant more, there will be more leaves, which will affect the distribution of light. Under high-density planting, the leaf area index (LAI) and intercepted effective light (IPAR) will increase, and the yield per unit area may increase. However, because the leaves below are blocked, the photosynthesis of each plant will become worse (Tao et al., 2018). If the density is appropriate, the light energy distribution will be more uniform, the efficiency of plant light utilization (RUE) will be higher, and the yield will naturally increase. However, if the planting is too dense and the shading is too severe, the RUE will become lower, and ultimately lead to a reduction in yield (Slattery and Ort, 2021). The study also found that the growth changes of wheat at high density are very similar to those in an environment with insufficient light, which shows that insufficient light is the main reason why density affects growth (Postma et al., 2021).

2.3 Hormonal signaling and resource allocation at different densities

Wheat can regulate its response to density through hormones. For example, when planted densely, the light perceived by the plant changes, especially the ratio of red light to far-red light becomes lower. This change will activate hormone signals in the body, causing the plant to change the way roots and branches grow (Wang et al., 2025). For example, when far-red light increases, a transcription factor called HY5 in the plant will increase, resulting in fewer lateral roots. This process affects the transport of auxin and how resources are allocated between roots and branches (Van Gelderen et al., 2018). Wheat will also decide whether to grow more roots or more branches based on signals such as root density and soil size, so that it can make good use of resources at different densities (Golan et al., 2024). In addition, some genetic factors, such as different versions of DELLA proteins, will also affect how wheat allocates nutrients in an environment with high density and low light, thereby affecting flowering and leaf growth.

3 Seedling Growth Dynamics under Varying Densities

3.1 Emergence rate and early vigor in response to sowing density

The number of wheat seedlings and early growth will be affected by sowing density and environmental conditions. The moisture, compactness and air circulation in the soil will directly affect the emergence. If there is enough water, the soil is not too hard, and the air is circulating, the wheat will grow fast and the seedlings will emerge evenly. However, if the soil is too hard or the crust is serious, especially when the seeds are planted very densely, the emergence will be poor (Hanks and Thorp, 1956; Liu et al., 2017). The early growth is generally determined by the height of the plant and the weight on the ground. If the fertilizer can keep up, the seedlings will grow fast. If the fertilizer is applied well in the early stage, it will also help to improve the growth. However, if the seeds are planted too densely, the seedlings will compete for water and nutrients, and each seedling will get less, and the growth will be worse (Mathlouthi et al., 2022).

3.2 Tillering capacity and shoot architecture

Whether wheat can produce more tillers will affect the structure of the stem. This is related to the variety and the density of planting. If the planting is too dense, the light and nutrients are insufficient, which will easily reduce the tillering of each seedling, but the branches will become straighter and more compact (Chen et al., 2025b). Although some varieties can produce more tillers when the density is high, most of the time, the higher the density, the fewer tillers each seedling has and the more compact the stems become. As a result, the yield of a single plant may decrease (Ter Steege et al., 2005).

3.3 Root system expansion and soil resource acquisition

Whether the wheat root system grows well in the early stage is particularly important for absorbing water and fertilizer later. When the wheat is planted densely, because there are many seedlings, the roots will compete for resources, so each seedling will have fewer roots. But overall, the total number of roots per square meter may be more (Colombi and Walter, 2017; Pflugfelder et al., 2022). More roots and more branches are a sign of strong seedlings and also help to absorb nutrients in the early stage. Some varieties can still grow good roots under stress or dense planting, which shows that genetics has an impact (Palta et al., 2007). The number and structure of roots can also be inherited, so they can be used to select better varieties that are more suitable for dense planting or poor soil conditions.

4 Influence on Final Yield Components

4.1 Effects on number of spikes per unit area

The higher the sowing density, the more wheat ears per square meter. Many studies have found that this is true for different varieties and different environments. When too few seeds are planted, the number of ears and yield are low; at medium or slightly higher density, the number of ears is large and the yield is the highest (Tian et al., 2025). But planting too densely is not a good thing. Competition is too fierce, and some tillers do not produce ears. Instead, they grow in vain, wasting nutrients, so the number of ears may not continue to increase (Kondić et al., 2017).

4.2 Grain number and grain weight variations

As the sowing density increases, the number of ears increases, and the number of grains naturally increases. However, this may make each grain lighter. Studies have shown that there is often a trade-off between the number of grains and the weight of grains: the more grains there are, the greater the proportion of small grains may be, which lowers the average grain weight (Acreche and Slafer, 2006; Xie and Sparkes, 2021). This phenomenon is affected by the variety and environment, and it is not only reflected in the whole plant, but also in the spikelets. Therefore, if you want a high yield, you must not only consider the number of grains, but also make sure that the grains are heavy enough and the density is just right (Li et al., 2016).

4.3 Harvest index and total biomass accumulation

The harvest index (HI) is the ratio of how much dry matter a plant distributes to its grains. The right density allows more nutrients to enter the ear, rather than being wasted on leaves and stems. When the density is higher, the total dry matter may be higher, but each plant may get less, and the grain weight may also decrease (Rivera-Amado et al., 2019). If the plant can deliver more nutrients to the ear during the flowering period, the fruit set rate will be high, the HI will be high, and the yield will be good. However, if the plant is planted too densely, the nutrients produced by photosynthesis are not enough for filling, and the HI will be lowered (Gao et al., 2025). Therefore, if you want to harvest more grain, you have to find a balance between density and nutrient distribution, so that dry matter can be accumulated more and distributed reasonably, and finally more and heavier grains can be produced.

5 Environmental and Management Interactions

5.1 Soil fertility and nutrient availability interactions with density

Soil fertility and fertilization methods affect the effect of sowing density on wheat growth. If the soil is not good and there is not enough fertilizer, planting too densely is not good. To improve this situation, organic fertilizers can be used together with chemical fertilizers, such as adding some manure or biochar, so that the soil is looser and has more nutrients, and the wheat roots grow better (Kumari et al., 2024; Ahmad et al., 2025). A strong root system is particularly important, especially in places with poor soil fertility, as it can help absorb more nutrients. And the fertilization method should not be random. A more balanced fertilizer management can make the soil and climate work better together and increase yields. But if you only focus on one type of fertilizer, it may be counterproductive (Wang et al., 2016).

5.2 Effects of climatic factors (e.g., temperature, rainfall)

Climate conditions, such as temperature, rainfall, and water availability, can also affect the effect of wheat planting density. Many years of follow-up studies have found that climate can cause large fluctuations in yield, but this effect can be smaller if fertilizers and management methods are kept up (Wei et al., 2021). For example, drought weather often makes high-density planting less effective. But some methods, such as inoculating arbuscular mycorrhizal fungi (AMF), can improve water use efficiency and grain filling in drought and low density (Duan et al., 2023). However, if there is a lot of water, such treatments may not help at high density, and may even have a counterproductive effect. Therefore, different regions must be managed according to actual conditions in order to cope with the problems caused by climate change (Wójcik-Gront et al., 2024).

5.3 Influence of agronomic practices (e.g., row spacing, irrigation)

How to set the row spacing, how to irrigate, and how to apply fertilizers will also affect the performance of wheat together with the sowing density. If the row spacing and watering are arranged properly, the roots can grow deeper

and wider, and the efficiency of absorbing water and fertilizer is also high, especially under the drip irrigation system (Li et al., 2021). The amount of fertilizers such as nitrogen and phosphorus should also be adjusted according to the density of planting. Only when they are well coordinated can the yield and resource utilization rate be increased (Kihara et al., 2022). In addition, some new practices, such as using biochar or inoculating AMF fungi, can also improve the soil and help crops grow better. These practices are particularly useful in alkaline soil or saline-alkali land (Ding et al., 2020). Therefore, at a time when climate change is becoming more and more obvious and resources are becoming more and more scarce, these measures are really critical to stabilizing wheat yields.

6 Case Study

6.1 Regional climatic and soil conditions relevant to wheat sowing

In Paraná, Brazil, researchers conducted field experiments in Londrina and Ponta Grossa. They wanted to understand how wheat grows under different climate and soil conditions. Weather changes, soil fertility, water content, and temperature in these places will affect wheat germination, growth, and yield. Similar experiments were also conducted in Shandong Province and the North China Plain in China. These studies illustrate a truth: if you want to grow well, you have to choose the right sowing time and density according to the local climate and soil (Wen et al., 2023).

6.2 Implementation of variable sowing densities and monitoring

In Brazil and China, the researchers selected different wheat varieties and tested different seed vigor conditions. They used sowing densities ranging from 150 to 450 grains per square meter to observe wheat seedling emergence, plant dry weight, ear number, green leaf index, and final yield. In Shandong, the sowing density ranged from 1.35 million to 4.05 million plants per hectare, and the research team also continued to track the changes in yield and quality in different ecological zones and sowing periods (Abati et al., 2018).

6.3 Observed outcomes: seedling vigor, yield performance, and economic return

When the seeds are more vigorous, the seedlings will emerge evenly and the seedlings will grow better, especially in places where the conditions are not so good. When less seeds are sown, each wheat plant can grow more aboveground parts; when more seeds are sown, although there are more seedlings, the growth of each plant may become weaker (Marinho et al., 2021). When the sowing density is adjusted to the appropriate range, such as 450 seeds/square meter in Brazil and 3.15 million plants per hectare in Shandong, the yield can be significantly improved. Because there are more ears, there are more grains. But planting too densely will reduce the quality of seeds and make each seed lighter. Studies have also found that the effect will be better if the sowing time is well coordinated. For example, Jining, Shandong, sowed on October 25, with a density of 3.15 million plants/hectare, and the yield and quality were ideal (Figure 2) (Chen et al., 2025a). Therefore, as long as the density is well selected and seeds with strong vitality are used, the yield and resource utilization efficiency can be improved, and the final benefits will be higher. In Brazil, the local BRS Sabiá and BRS Gralha Azul varieties performed best in their respective regions, indicating that varieties must be matched with the environment. In China, different regions also adopted different sowing strategies, ensuring both high yield and high quality, and helping farmers earn more.

7 Advances in Precision Agriculture and Sowing Density Optimization

7.1 Use of remote sensing and UAVs to monitor crop density and performance

Nowadays, many people use remote sensing technology to farm, especially drones. The pictures taken by drones are clear, fast, and can be taken frequently, which allows us to better understand the density, growth and health of crops. Many drones are equipped with RGB, multispectral, hyperspectral or laser radar (LiDAR) sensors, which can help us draw very detailed crop distribution maps (Maes and Steppe, 2019; Omia et al., 2023). With these maps, we can see clearly which fields have uneven seedlings, which fields are growing slowly, and which fields may be under pressure. In this way, different management methods can be made according to different situations, and the seed density can be adjusted more appropriately to increase both yield and resource utilization (Mesas-Carrascosa, 2020).

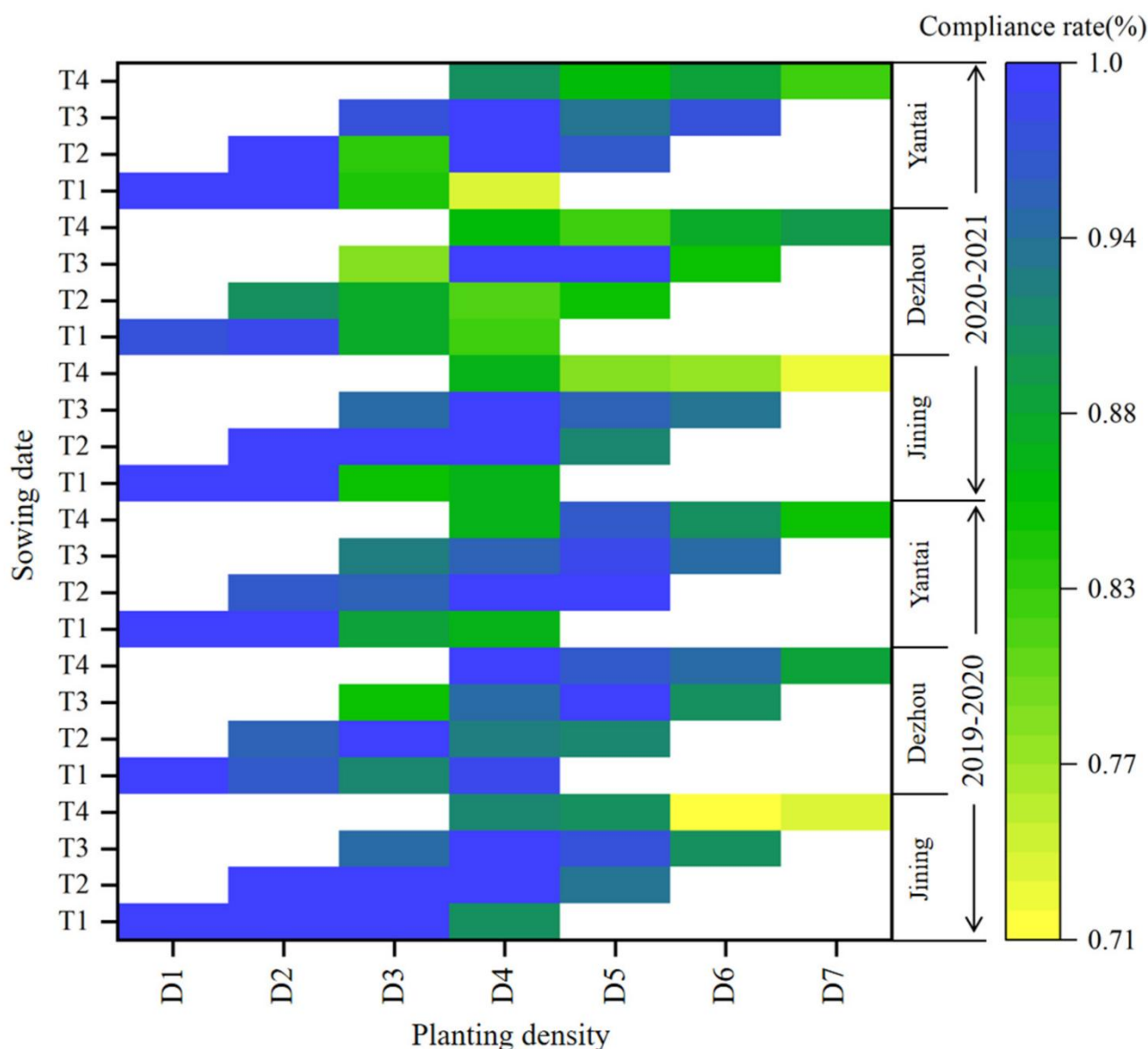


Figure 2 Analysis of sample quality compliance rate (Adopted from Chen et al., 2025a)

Image caption: T1, T2, T3, and T4 indicate that the sowing date was October 5, October 15, October 25, and November 5, respectively; D1, D2, D3, D4, D5, D6, and D7 indicate that the planting density was 135, 180, 225, 270, 315, 360, 405 $\times 10^4$ plants ha^{-1} , respectively (Adopted from Chen et al., 2025a)

7.2 AI and modeling approaches to predict optimal sowing rates

Some people are now using artificial intelligence (AI) to analyze these remote sensing images and field data. AI models, such as convolutional neural networks (CNN) and long short-term memory networks (LSTM), can analyze the growth of crops from sequences of drone photos and predict how much grain they can produce and how many leaves they can grow (Han et al., 2019; Nevavuori et al., 2020). If you do some experiments in the field and combine them with spatial modeling, you can tell you more accurately which plots of land should be planted more densely and which plots should be planted more sparsely. Doing so can achieve the best results for different plots of land and make more money (Istiak et al., 2023).

7.3 Integration with variable-rate seeding technologies

Variable Rate Seeding (VRS) technology adjusts seed density based on the actual conditions of each field, such as soil texture, pH, and previous yield data. VRS combines remote sensing, AI analysis, and field data to determine the most appropriate planting method (Sishodia et al., 2020; Šarauskis et al., 2022). This system uses sensors and mapping tools to find out where yields are limited and then automatically controls the seeding rate of the seed drill.

It now appears that using VRS can help farmers use less seeds and still get the same or even better harvests. This is particularly cost-effective for large farms because it can save money and increase production (Loewen and Maxwell, 2024).

8 Challenges and Knowledge Gaps

8.1 Lack of region-specific density recommendations

A big problem now is that many places have not yet given recommendations on wheat sowing density suitable for their local areas. In fact, the climate, soil and farming methods in different regions are different. For example, how much sunlight, whether it rains or not, and whether the temperature is high or not, all of these will affect which density is most suitable (Wu et al., 2023). Studies have found that if the density can be adjusted according to local conditions, the yield and resource utilization rate will be greatly improved. But in reality, wheat planting often does not have such "adapting to local conditions" guidance. Farmers can only sow based on experience, which makes it difficult to achieve high yields and good efficiency, and is not conducive to their response to climate change.

8.2 Difficulty in balancing trade-offs between yield and input use efficiency

It has always been difficult to achieve high yields without wasting water and fertilizer. Although increasing the density may produce more grain, if it is not managed well, water and fertilizer may be wasted and even pollute the environment (Dong et al., 2020; Zhang et al., 2021). In some high-yield areas of wheat-corn continuous cropping, too much nitrogen fertilizer is often used, resulting in low nitrogen fertilizer utilization and harm to the environment. Currently, only a small number of farmers can achieve high yields without wasting fertilizer (Li et al., 2019; Xu et al., 2023). To strike a good balance, supporting management methods are needed, and farmers should be taught more about how to use fertilizers and how to control water use (Dai et al., 2023).

8.3 Limited long-term studies across crop rotations and seasons

Most current studies on seeding density are short-term and focus on only one crop. Such studies cannot reflect the real impacts on soil, water use, and yields over time, such as after several years of rotation (Zhang et al., 2025). Long-term wheat-corn rotation experiments and model analysis have shown that the effects of fertilizer flow and crop sequence between seasons must be considered to achieve stable yields and rational resource use (Cui et al., 2022). However, to truly provide farmers with practical rotation density recommendations, more long-term, cross-crop in-depth studies are needed to see whether these strategies are reliable in different years and different planting methods.

9 Concluding Remarks

Choosing the right wheat sowing density is very important, as it affects how well the seedlings grow, whether the leaves shade the wheat properly, and whether more grain can be harvested in the end. Generally speaking, a medium density (e.g., 270 to 300 plants per square meter) works best. This density allows wheat to grow faster, leaves to be better distributed, light and nutrient utilization to be higher, and the final yield to be higher than planting too much or too little. If the density is too high, each seedling will grow weak, the grains will become lighter, and it will be more likely to fall over; if the density is too low, although the seedlings grow strong, the number of ears will not be enough, and the yield will not increase. Therefore, it is particularly important to find the most suitable density. However, different varieties, climates, soils, and management methods have different suitable densities. But as long as the right choice is made, fertilizer, water, and light can be used more efficiently and the yield will be more stable.

We should formulate specific sowing density recommendations for different regions and varieties, and also combine them with local climate, soil, and planting methods. Appropriately increasing sowing density and applying less nitrogen fertilizer can also ensure yield while making nitrogen fertilizer more economical and more environmentally friendly. We can try some new methods, such as wide strip planting, combined with density adjustment to improve light utilization and yield. In addition, more long-term research is needed to see how density management affects soil, yield and sustainability under different rotation methods. Using precision agriculture tools such as remote sensing and modeling can also better see how crops are growing, and then adjust the sowing amount according to the differences in plots, making management more flexible.

In general, if you want to grow wheat well and harvest more, you have to start with sowing density. As long as management is based on local conditions and combined with advanced technology, farmers can increase yields, use more resources, and better cope with climate change. In the future, we must continue to study these methods and promote precision agriculture tools so that more people can benefit from them.

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Conflict of Interest Disclosure

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

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