Triticeae Genomics and Genetics, 2025, Vol.16, No.2, 92-100
http://cropscipublisher.com/index.php/tgg

Research Insight Open Access

Optimizing Sowing Density and Nitrogen Management for Yield Maximization in Bread Wheat

Zhongying Liu, Wei Wang
Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China
Corresponding email: wei.wang@jicat.org

Triticeae Genomics and Genetics, 2025, Vol.16, No.2 doi: 10.5376/tgg.2025.16.0010
Received: 02 Mar., 2025
Accepted: 12 Apr., 2025
Published: 28 Apr., 2025

Preferred citation for this article:
Liu Z.Y., and Wang W., 2025, Optimizing sowing density and nitrogen management for yield maximization in bread wheat, Triticeae Genomics and Genetics, 16(2): 92-100 (doi: 10.5376/tgg.2025.16.0010)

Abstract Sowing density and nitrogen fertilizer management are key agronomic measures that determine wheat yield and nitrogen fertilizer utilization efficiency. To determine the optimal combination of the two, this study comprehensively analyzed the effects of different sowing densities and nitrogen application levels on the population structure, root development, photosynthetic characteristics and yield components of bread wheat. Taking the North China Plain, the Indo-Ganges Plain and the semi-arid region of the Middle East as representative areas, a comprehensive exploration was further conducted on the yield formation process and resource utilization mechanism. The research results show that a medium to high seeding density (300-400 grains /m^2) combined with an appropriate amount of nitrogen fertilizer (150-200 kg/ha) and fractional nitrogen application management can significantly increase the number of effective ears, dry matter accumulation and nitrogen utilization efficiency, thereby maximizing yield, while reducing nitrogen loss and greenhouse gas emissions. Compared with traditional high-nitrogen management, this optimized model can enhance economic benefits, improve grain quality, and promote the green transformation of agriculture. This study not only reveals the mechanism by which sowing density and nitrogen fertilizer management interact with each other in terms of yield formation and resource utilization, but also proposes an integrated management model for high-yield and sustainable wheat production adapted to different ecological regions, with the expectation of promoting wheat production practice, narrowing the yield gap, and achieving food security and ecological protection.

Keywords Bread wheat; Sowing density; Nitrogen fertilizer management; Yield improvement; Nitrogen fertilizer use efficiency

1 Introduction

Wheat (*Triticum aestivum* L.) is a very important food crop worldwide and plays a key role in ensuring that people have enough to eat. Nowadays, people's demands for agriculture are not only high yields but also more sustainable. Therefore, increasing wheat production has become one of the key focuses of modern agricultural work. With the continuous increase in population, we not only need to grow more wheat and harvest it steadily, but also minimize the harm to the environment and the waste of resources as much as possible.

Among all planting management methods, sowing density and nitrogen fertilizer application are two key factors influencing the growth, yield and grain quality of wheat. Adjusting the sowing density will affect the number of tillers, the number of spikes, and also influence whether the plants in the field grow neatly. The application of nitrogen will directly affect the growth volume, protein content of grains and yield composition of plants. There is also an interaction between these two factors. They not only affect yield, but also relate to the efficiency of resource utilization and the adaptability of crops in the face of environmental pressure (Marinho et al., 2022; Mu et al., 2024; Tian et al., 2024; Gao et al., 2025; Shi et al., 2025).

Recent research indicates that for wheat to be both high-yielding and environmentally friendly, both sowing density and nitrogen fertilizer input need to be taken into account simultaneously; one factor alone cannot be considered. When the two are well combined, they can not only increase the yield of wheat, but also make the use of nitrogen fertilizer more effective and maintain the quality of the grain without being affected. This study will explore the effects of different sowing densities and nitrogen application rates on wheat yield and quality, analyze the physiological and agronomic mechanisms behind these effects, and provide practical suggestions for maximizing yield and sustainability in different agricultural ecological environments. By integrating physiological,

ecological and management factors, this study aims to provide a scientific basis for high-yield wheat cultivation, while promoting efficient resource utilization and sustainable agricultural development.

2 Physiological Basis of Sowing Density and Nitrogen Interaction

2.1 Effects of plant density on canopy development and light interception

When the planting density is high, the plants will form rows more quickly and the canopy will become tighter. In this way, the leaf area index (LAI) will increase, allowing more sunlight to be blocked, and the photosynthetic efficiency of the population will also be higher (Figure 1) (Zhang et al., 2021; Shi et al., 2025). However, if the density is too high, the growth of individual plants will weaken, and light will not easily reach the lower leaves, and the photosynthesis of the lower leaves will deteriorate. Finding an appropriate density can increase the number of effective tillers and ears, thereby helping to enhance the final yield (Yang et al., 2019; Zhou et al., 2024).

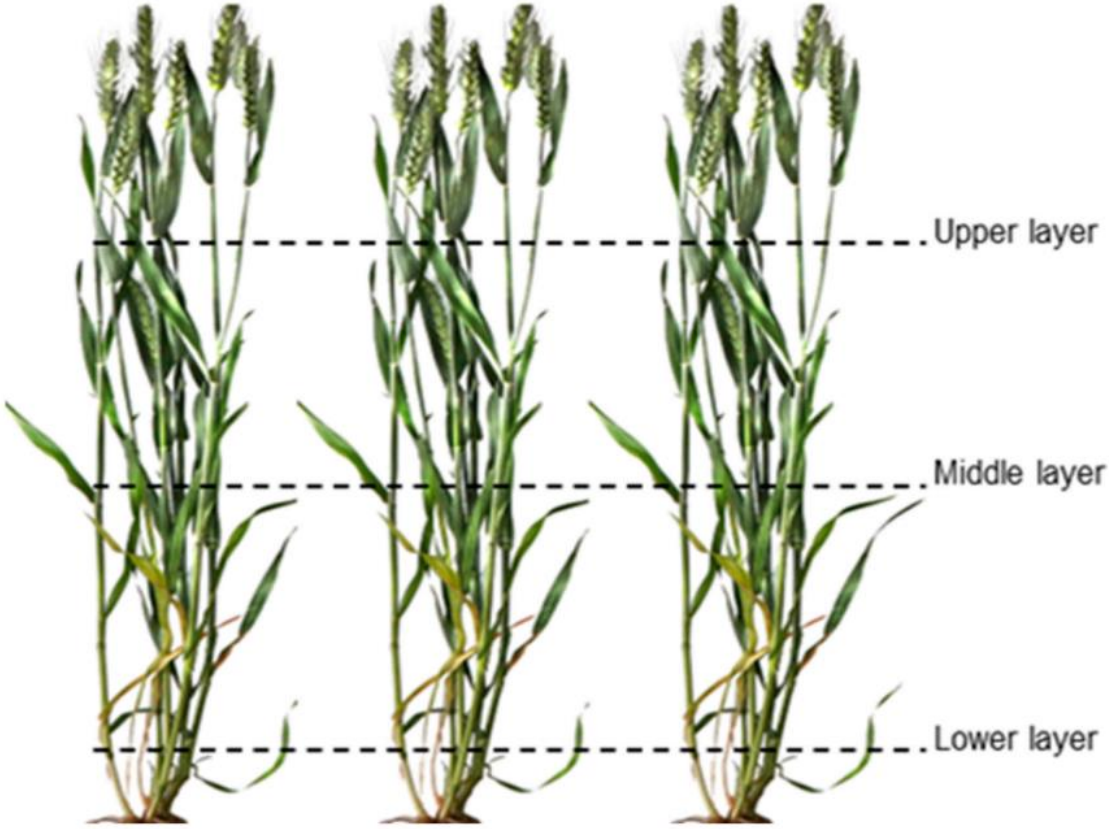

Figure 1 Schematic diagram of the canopy stratification of winter wheat (Adopted from Shi et al., 2025)

2.2 Nitrogen's role in photosynthesis and grain filling

Nitrogen is an important element in the formation of chlorophyll and directly affects the efficiency of photosynthesis. It also has a significant impact on the grain filling process (Mashiqa et al., 2022). When there is sufficient nitrogen fertilizer, the content of chlorophyll will increase, the speed of photosynthesis will accelerate, light energy will be more easily converted into nutrients, and the development of grains will also be better (Wang et al., 2024). However, excessive nitrogen fertilizer, especially when the density is high, can easily disrupt the hormones and balance within the plant, causing the filling of weak grains to slow down and the grain weight to decrease (Liu et al., 2020).

2.3 Interactive influence on biomass accumulation and partitioning

Density and nitrogen fertilizer affect each other. They determine whether crops use more nutrients for growing leaves and roots or for filling and seed setting. When the density is moderate and the nitrogen fertilizer is well controlled, the roots will grow more and deeper, which can absorb more nitrogen from the soil, help accumulate

more dry matter and improve the utilization efficiency of nitrogen (Dai et al., 2014; Dong et al., 2020). Increasing density can to some extent compensate for the impact of insufficient nitrogen fertilizer, but if the nitrogen or density is too high, crops will distribute more nutrients to the stems and leaves, which will instead affect grain development and lead to a decline in yield and quality (Zheng et al., 2022). Only by finding the appropriate density and nitrogen fertilizer dosage can the maximum accumulation of dry matter be achieved, and nutrients be effectively distributed to the grains, thus realizing high yields and efficient resource utilization.

3 Effects on Root Architecture and Resource Uptake

3.1 Root length density and rooting depth under different sowing densities

After the sowing density increases, the root length density (RLD) of the population will increase, especially in the upper soil layer. This is because when the density is high, more node roots will grow in each plant and each plot (Wang et al., 2024). After the density increases, the number of roots in the deep soil (such as 0.8 to 1.2 meters) will also increase, enabling crops to absorb more water and nutrients from the deep layers (Dai et al., 2014; Dong et al., 2020). However, although the number of roots in the entire plot has increased, the root systems of individual plants may become smaller.

3.2 Nitrogen-driven changes in root morphology and function

Nitrogen application can promote better root growth, increasing both the length and weight of roots, especially in the topsoil (Mehrabi et al., 2021). If more nitrogen fertilizer is used, the surface area of the roots and the number of root tips will also increase, and the absorption capacity will be stronger (Zhang et al., 2021). Nitrogen can also affect the functions within roots, such as altering the activities of nitrate reductase and glutamine synthase, which are related to the absorption and transformation of nitrogen (Tian et al., 2024). However, the effect of nitrogen is also influenced by soil moisture and planting methods.

3.3 Combined impact on water and nutrient absorption efficiency

When the sowing density and nitrogen fertilizer combination are reasonable, the root system of wheat will be more developed and can absorb water and nutrients from more layers of soil. For instance, if the row spacing is increased or the sowing method is improved, the number, length and surface area of roots will all increase, especially in deep soil. This can enhance the absorption efficiency of nitrogen without affecting the yield (Zheng et al., 2023). These practices can enhance the utilization rate of nitrogen fertilizers, maintaining or even increasing yields while reducing fertilization, which is beneficial for the sustainable cultivation of wheat.

4 Results and Analysis of Yield Performance

4.1 Grain yield response under varying sowing densities

When the sowing density increases, the number of ears in the field will rise and the yield will generally increase, especially when nitrogen fertilizer is used appropriately. However, too high a density can cause problems. The number of grains on each spike may decrease, and the 1000-grain weight will also decline. The grain filling is not good enough, and the middle spikelets are most affected (Liu et al., 2020). Generally speaking, a medium-high density (300 to 400 grains per square meter) is the most likely to achieve high yields. If the density is further increased, the output will not only fail to rise but may even decline (Sun et al., 2023).

4.2 Nitrogen-use efficiency and yield correlation

If nitrogen fertilizer is used well, the yield of wheat can be increased and the quality of the grains will also be better. However, if too much is applied, not only will the yield not increase, but the utilization efficiency of nitrogen fertilizer will also decrease. Some studies have found that when the sowing density is high, less nitrogen fertilizer can be applied, but the yield and utilization efficiency can still be maintained at a good level. This is because of its high density, which leads to a larger root system and better absorption of nitrogen from the soil (Dong et al., 2020; Zhou et al., 2024). Generally speaking, it is a reliable approach to apply nitrogen fertilizer in several portions and keep the total amount at 100 to 200 kilograms per hectare. This method can stabilize the yield, increase the protein content, and at the same time have a small impact on the environment (Jarecki, 2024; Lachutta and Jankowski, 2024).

4.3 Optimization of density–nitrogen combinations for yield maximization

For wheat to grow well and yield a high yield, it is also necessary to use nitrogen fertilizer appropriately. The planting density and fertilization methods should be well-matched. Many studies have pointed out that the most ideal effect is achieved by using a medium or slightly higher density and combining it with fractional fertilization (Dong et al., 2020; Wang et al., 2023). For instance, research has found that when the planting density increased from 750,000 plants per hectare to 3.36 million plants and the nitrogen fertilizer application was 290 kilograms, both the yield and nitrogen utilization rate reached the optimal level (Yang et al., 2019). When some people were studying weak-gluten wheat, they found that if 3 million plants were planted per hectare and 48.6 kilograms of fertilizer were applied, it could also perform well (Zhou et al., 2024). These methods can regulate the number of tillers, making the ears grow better and also contribute to the accumulation of dry matter. In this way, the output can be increased and the use of nitrogen fertilizer will be more efficient. Therefore, if you want to achieve high wheat yields and avoid wasting nitrogen fertilizer, the density and fertilization must be well balanced. With a slightly higher density and well-controlled fertilization methods, not only can the yield be maintained, but also waste can be reduced, the quality of grains can be improved, and it is more environmentally friendly.

5 Agronomic and Physiological Trait Evaluation

5.1 Plant height, tillering, and leaf area index

Sowing density and nitrogen application rate will directly affect the plant height and tillering number of wheat. When 300 to 400 grains are sown per square meter, the number of tillers in the field will increase, and the final number of ears formed will also rise. Although this might slightly reduce the number of grains per spike, on the whole, the total output can still be increased. If nitrogen is applied in addition, the tillers will grow faster, the leaves will become larger, the leaf area index will increase, and the photosynthetic efficiency will be higher. This will make the plants grow more vigorously and have a larger biomass (Novruzov and Allahverdiyev, 2023). However, the height of plants is not only determined by density and nitrogen fertilizer, but also related to the variety and weather. For some wheat varieties, under high-density planting and excessive fertilization, the plant height will increase significantly and the flag leaves will also become longer.

5.2 Harvest index and nitrogen uptake efficiency

If the sowing time is slightly later and nitrogen is applied in reasonable portions, the harvest index can increase by 5% to 7%, indicating that more nutrients are used on the grains (Lachutta and Jankowski, 2024). An appropriate amount of nitrogen fertilizer can promote nutrient accumulation and enhance the efficiency of nitrogen absorption and utilization. Generally speaking, when there is more nitrogen fertilizer, the grain yield and protein content will be higher (Ivicet al., 2021; Farooq et al., 2024; Li et al., 2025). However, different varieties performed differently. Some varieties had a higher nitrogen utilization rate and better yield performance under the condition of applying more nitrogen (Desai et al., 2024).

5.3 Lodging resistance and spike number per unit area

As long as the sowing density is appropriate and the fertilization method is used correctly, the number of ears per square meter can be increased. When there are more ears, the yield will naturally be higher. This is one of the key factors affecting output. However, if they are planted too densely or too much fertilizer is used, the plants may grow too tall and are prone to toppling over. Especially when encountering varieties that are not resistant to toppling or when the fertilizer is not evenly spread, the situation will be even worse. Studies have shown that sowing 400 seeds per square meter and applying nitrogen fertilizer in stages yields the best results. This approach can increase production while minimizing the risk of overturning (Novruzov and Allahverdiyev, 2023; Lachutta and Jankowski, 2024). Besides, wheat with thick stems is less likely to fall over than thin ones. The thickness of the stem is also related to the density of the species and the type of variety (Pinheiro et al., 2019).

6 Case Studies: Field Implementation Across Regions

6.1 North China Plain: moderate density with split nitrogen application

In the experiments in the North China Plain, it was found that medium-density sowing had a good effect. For instance, it would be appropriate to plant 300 to 400 seeds per square meter. Nitrogen fertilizer should not be

applied all at once but in several portions, which is more effective. For instance, first apply 100 kilograms per hectare during the tillering stage, and then add 40 kilograms during the jointing stage. This approach enables more tillers to grow into ears, and the yield will naturally increase. Medium-density planting can also make the distribution of wheat more even, the grains grow fuller, and there will be no uneven sizes. Staged nitrogen application can also increase the protein content in the grains and improve the quality of the flour. Especially when sowing is delayed by two or three weeks, this method performs more stably (Lachutta and Jankowski, 2024).

6.2 Indo-Gangetic Basin: high-density precision sowing under nitrogen-saving mode

In high-yield and heavily cultivated regions such as the Indus and Ganges River basins, increasing the sowing density (405 plants per square meter) can reduce the amount of nitrogen fertilizer used without lowering the yield. High density can make the root systems of crops more developed, absorb more nitrogen, and thus maintain high yields. In addition, precise sowing can also make up for the impact of reduced nitrogen fertilizer. This can not only ensure the output but also save resources, which is very helpful for sustainable agriculture (Dong et al., 2020).

6.3 Middle East semi-arid zone: adaptive density with water-nitrogen integration

The climate in the Middle East is dry, with little water and not very fertile soil. So when growing wheat here, how to combine water and nitrogen fertilizer is very crucial. Experiments show that keeping the planting density at around 3.6 million plants per hectare, along with appropriate irrigation and the use of furrow and ridge planting methods, yields better results. This can enable water and nitrogen fertilizers to play their roles more fully, and the resources in the soil can also be better utilized. Not only did the output increase in the end, but this method also stabilized the harvest in years of drought, ensuring that farmers did not suffer losses (Figure 2) (Dai et al., 2023).

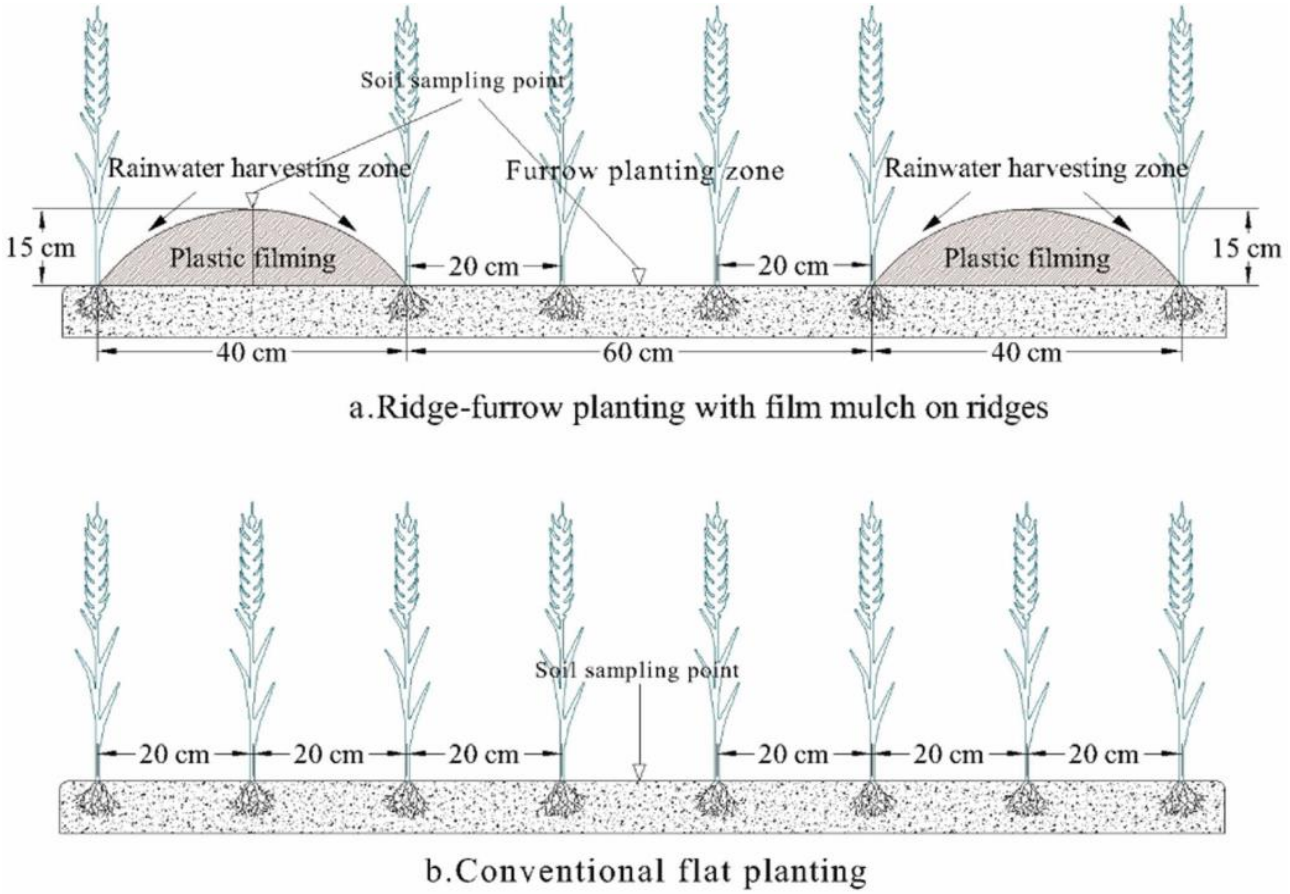

Figure 2 Planting patterns of winter wheat and soil sampling positions during the 2020-2021 and 2021-2022 growing seasons (Adopted from Dai et al., 2023)

7 Environmental and Sustainability Considerations

7.1 Minimizing nitrogen losses and environmental pollution

Excessive use of nitrogen fertilizer can cause environmental pollution. It will increase greenhouse gas emissions and also allow nitrates to enter groundwater. Research has found that applying only the nitrogen fertilizer that crops truly need can not only maintain yields but also significantly reduce the costs of nitrogen loss and environmental damage (Cui et al., 2010; Bernas et al., 2023). Compared with traditional methods, applying fertilizers in stages or seasonally based on soil test results can better reduce the loss of excessive nitrates and nitrogen in the soil (Zhang et al., 2019). Generally speaking, using 100 to 150 kilograms of nitrogen fertilizer per hectare has the least impact on the environment. Too much or too little nitrogen fertilizer will increase emissions and pollution. The research also found that the combined management of water and fertilizer could reduce ammonia volatilization by 72% and nitrous oxide emissions by 57% (Huang et al., 2024).

7.2 Sowing density and weed suppression potential

Increasing the sowing density can make crops grow faster and the ground cover up more quickly. In this way, the weeds won't get sunlight and their growth will slow down, so less herbicides can be used. This can not only save money, but also slow down the development of weed resistance and protect the ecological environment of farmland. Close planting can also make the soil structure more stable, reduce soil erosion, and promote the sustainable development of agriculture from the side.

7.3 Sustainable intensification for smallholder systems

Some methods, although seemingly simple, are really useful for small-scale farmers. For instance, the sowing time can be slightly advanced or delayed. Scatter more seeds; Apply the nitrogen fertilizer in several portions. Be careful not to water too much when watering. These practices are not difficult to learn and do not require any high technology. Farmers can easily get started. There are many benefits to doing so. Not only can it make crops grow better, but also increase the yield and improve the utilization rate of nitrogen fertilizer. Moreover, the income and expenditure of nitrogen will also become more balanced. The most crucial point is that this can save unnecessary money, reduce costs, and also significantly reduce the pressure on the environment (Zhang et al., 2019; Huang et al., 2024). These simple yet practical methods are also in line with the Sustainable Development Goals advocated by the United Nations. Especially in some small farms with relatively scarce resources, this approach is more suitable for promotion (Fu et al., 2023; Du et al., 2024). From the practical results in some places, it can be seen that after adopting these comprehensive management methods, not only has the grain output increased, but the utilization of water and fertilizers has also become more efficient. Because it is used more accurately, the emissions of greenhouse gases have also decreased significantly. In this way, farmers can not only make money but also protect the environment well, taking care of both the economy and the ecology (Xu et al., 2023).

8 Concluding Remarks

Research has generally found that moderate or high sowing density, combined with an appropriate amount of nitrogen fertilizer (usually less than traditional methods), can significantly increase grain yield, nitrogen fertilizer utilization efficiency and economic income. At the same time, it can also reduce harm to the environment. Dividing fertilization into several sessions, choosing the right time, and combining irrigation and fertilization can also help improve the stability of yields and the efficiency of resource utilization. High-yield planting systems often benefit from more ears and a neater population structure. However, if the density or the amount of nitrogen fertilizer used is too high, it may lead to a decline in the quality of the grains or make them more prone to lodging.

Reasonable arrangement of planting density and application of nitrogen fertilizer can not only increase yield but also make the use of nitrogen fertilizer more effective. If well combined, it can also reduce excessive nitrogen, lower greenhouse gas emissions, and minimize nutrient loss. This approach is particularly useful for small-scale farmers or areas with limited resources. It can ensure output while narrowing the gap between high and low yields, and also protect the environment. The rational combination of water and nitrogen, coupled with the improvement of soil conditions, is also crucial for the long-term development of agriculture. These practices are also helpful in addressing climate change.

The following research should focus on improving some agricultural models, such as DSSAT and APSIM. At present, these models are not good enough in handling the relationships among varieties, the environment and management measures. We need to enable them to better integrate with the local soil and climate conditions, and also take into account the requirements of sustainable development. In terms of promotion, we need to assist farmers in mastering the appropriate planting density and fertilization methods, such as how to apply fertilizers in batches, how to sow precisely, or how to carry out integrated water and fertilizer management. At the same time, policymakers should also encourage farming methods that can both ensure farmers' income and reduce environmental impact. It is also necessary to promote the method of using data to guide agricultural management and encourage more farmers to give it a try. If we want to achieve high and stable wheat yields while developing sustainable agriculture, it is necessary to optimize planting density and the use of nitrogen fertilizers. To achieve this, it still depends on better models, farmers' participation, and reasonable policy support.

Acknowledgments

We are grateful to Dr. Z. Xu for his assistance with the serious reading and helpful discussions during the course of this work.

Conflict of Interest Disclosure

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

References

Bernas J., Koppensteiner L., Tichá M., Kaul H., Klimek-Kopyra A., Euteneuer P., Moitzi G., and Neugschwandtner R., 2023, Optimal environmental design of nitrogen application rate for facultative wheat using life cycle assessment, European Journal of Agronomy, 146: 126813.
https://doi.org/10.1016/j.eja.2023.126813

Cui Z., Zhang F., Chen X., Dou Z., and Li J., 2010, In-season nitrogen management strategy for winter wheat: Maximizing yields, minimizing environmental impact in an over-fertilization context, Field Crops Research, 116: 140-146.
https://doi.org/10.1016/J.FCR.2009.12.004

Dai X., Xiao L., Jia D., Kong H., Wang Y., Li C., Zhang Y., and He M., 2014, Increased plant density of winter wheat can enhance nitrogen-uptake from deep soil, Plant and Soil, 384: 141-152.
https://doi.org/10.1007/s11104-014-2190-x

Dai Y., Liao Z., Lai Z., Bai Z., Zhang F., Li Z., and Fan J., 2023, Interactive effects of planting pattern, supplementary irrigation and planting density on grain yield, water-nitrogen use efficiency and economic benefit of winter wheat in a semi-humid but drought-prone region of northwest China, Agricultural Water Management, 287: 108438.
https://doi.org/10.1016/j.agwat.2023.108438

Desai P., Biradar P., Patil P., Sanjay P., Singh P., Naik P., Lamani P., Joshi P., Singh S., and Asia S., 2024, Nitrogen use efficiency in bread wheat: genetic variation and prospects for improvement, PLOS ONE, 19(4): e0294755.
https://doi.org/10.1371/journal.pone.0294755

Dong S., Zhang J., Zha T., Dai X., and He M., 2020, Increased plant density with reduced nitrogen input can improve nitrogen use efficiency in winter wheat while maintaining grain yield, Archives of Agronomy and Soil Science, 66: 1707-1720.
https://doi.org/10.1080/03650340.2019.1690139

Du C., Liu Y., Guo J., Zhang W., Xu R., Zhou B., Xiao X., Zhang Z., Gao Z., Zhang Y., Sun Z., Zhou X., and Wang Z., 2024, Novel annual nitrogen management strategy improves crop yield and reduces greenhouse gas emissions in wheat-maize rotation systems under limited irrigation, Journal of Environmental Management, 353: 120236.
https://doi.org/10.1016/j.jenvman.2024.120236

Farooq, Nazar M., Akbar M., Ghafoor T., Shabir M., Rafique H., Qamar M., Qazi M., Aslam Z., Hafeez Z., Manzoor N., Hassan W., Khaliq A., Murtaza G., Rehman S., Mubashir M., Bashir M., Arif M., Asif M., Imran M., Khalid M., and Hussain S., 2024, Impact of varied amounts of nitrogenous fertilizers on grain yield and related agro-physiological traits in spring wheat (*Triticum aestivum* L.), Biological and Clinical Sciences Research Journal, 5(1): 1196.
https://doi.org/10.54112/bcsrj.v2024i1.1196

Fu Z., Zhang K., Zhang J., Cao Q., Tian Y., Zhu Y., Cao W., and Liu X., 2023, Optimizing nitrogen application and sowing date can improve environmental sustainability and economic benefit in wheat-rice rotation, Agricultural Systems, 204: 103536.
https://doi.org/10.1016/j.agsy.2022.103536

Gao Y., Wang Q., Liu Y., He J., Chen W., Xing J., Sun M., Gao Z., Wang Z., Zhang M., and Zhang Y., 2025, Optimal water, nitrogen, and density management increased wheat yield by improving population uniformity, Agricultural Water Management, 310: 109362.
https://doi.org/10.1016/j.agwat.2025.109362

Huang X., Xu X., Zhu Q., and Zhang Y., 2024, Optimizing water and nitrogen inputs for sustainable wheat yields and minimal environmental impacts, Agricultural Systems, 220: 104061.
https://doi.org/10.1016/j.agsy.2024.104061

Ivić M., Grljušić S., Plavšin I., Dvojković K., Lovrić A., Rajković B., Maričević M., Černe M., Popović B., Lončarić Z., Bentley A., Swarbreck S., Šarčević H., and Novoselović D., 2021, Variation for nitrogen use efficiency traits in wheat under contrasting nitrogen treatments in South-Eastern Europe, Frontiers in Plant Science, 12: 682333.
https://doi.org/10.3389/fpls.2021.682333

Jarecki W., 2024, Response of winter wheat to delayed sowing and varied nitrogen fertilization, Agriculture, 14(1): 121.
https://doi.org/10.3390/agriculture14010121

Lachutta K., and Jankowski K., 2024, An agronomic efficiency analysis of winter wheat at different sowing strategies and nitrogen fertilizer rates: a case study in Northeastern Poland, Agriculture, 14(3): 442.
https://doi.org/10.3390/agriculture14030442

Li Y., Zhao S., Liu G., Li J., Siddique K., and Zhao D., 2025, Agronomic traits, nutrient accumulation, and their correlations in wheat, as affected by nitrogen supply in rainfed coastal saline soils, Plants, 14(7): 1022.
https://doi.org/10.3390/plants14071022

Liu Y., Liao Y., and Liu W., 2020, High nitrogen application rate and planting density reduce wheat grain yield by reducing filling rate of inferior grain in middle spikelets, The Crop Journal, 9(2): 412-426.
https://doi.org/10.1016/J.CJ.2020.06.013

Marinho J., Silva S., Fonseca I., and Zucareli C., 2022, Nitrogen fertilization and sowing density on yield and physiological quality of wheat seeds, Journal of Seed Science, 44: e202244013.
https://doi.org/10.1590/2317-1545v44254717

Mashiqa P., Pule-Meulenberg F., and Ngwako S., 2022, Wheat growth as affected by planting density, Planting Time and Nitrogen Application, 1: 1-20.
https://doi.org/10.21203/rs.3.rs-1276650/v1

Mehrabi F., Sepaskhah A., and Ahmadi S., 2021, Winter wheat root distribution with irrigation, planting methods, and nitrogen application, Nutrient Cycling in Agroecosystems, 119: 231-245.
https://doi.org/10.1007/s10705-021-10120-1

Mu H., Wang Z., Sun L., Huang Y., Song Y., Zhang R., Wu Z., Fu K., Duan J., Kang G., Guo T., and Wang Y., 2024, Optimizing nitrogen fertilization and planting density management enhances lodging resistance and wheat yield by promoting carbohydrate accumulation and single spike development, Crop Science, 64(6): 3461-3479.
https://doi.org/10.1002/csc2.21327

Novruzov L., and Allahverdiyev T., 2023, Effect of different doses and application types of nitrogen fertilizer on some physiological and agronomical parameters of bread wheat genotypes, Transactions of the Institute of Molecular Biology & Biotechnologies, 7(2): 62-67.
https://doi.org/10.62088/timbb/7.2.9

Pinheiro M., Souza C., Fioreze S., C., J., and Bisato M., 2019, Agronomic performance of wheat cultivars under different sowing densities in Southern Brazil, Journal of Experimental Agriculture International, 39(6): 1-16.
https://doi.org/10.9734/JEAI/2019/V39I630350

Shi Z., Mao T., L., Pan H., Liu J., Wang D., Yang L., and Zhai Y., 2025, Effects of delayed application of nitrogen fertilizer on yield, canopy structure, and microenvironment of winter wheat with different planting densities, Agronomy, 15(2): 502.
https://doi.org/10.3390/agronomy15020502

Sun Y., Yang W., Wu Y., Cui Y., Dong Y., Dong Z., and Hai J., 2023, The effects of different sowing density and nitrogen topdressing on wheat were investigated under the cultivation mode of hole sowing, Agronomy, 13(7): 1733.
https://doi.org/10.3390/agronomy13071733

Tao Z., Ma Y., Chang X., Wang D., Wang Y., Yang Y., Zhao G., and Yang J., 2019, Effects of tridimensional uniform sowing on water consumption, nitrogen use, and yield in winter wheat, The Crop Journal, 7(4): 480-493.
https://doi.org/10.1016/J.CJ.2018.12.006

Tian Z., Yin Y., Li B., Zhong K., Liu X., Jiang D., Cao W., and Dai T., 2024, Optimizing planting density and nitrogen application to mitigate yield loss and improve grain quality of late-sown wheat under rice-wheat rotation, Journal of Integrative Agriculture, 24(7): 2558-2574.
https://doi.org/10.1016/j.jia.2024.01.032

Wang Y., Li W., Deng Y., Xue J., and Gao Z., 2024, Higher seed rates enlarge the effects of wide-belt sowing on root length density, thereby improving nitrogen uptake and use efficiencies in winter wheat, Plants, 13(17): 2476.
https://doi.org/10.3390/plants13172476

Wang Y., Peng Y., Lin J., Wang L., Jia Z., and Zhang R., 2023, Optimal nitrogen management to achieve high wheat grain yield, grain protein content, and water productivity: a meta-analysis, Agricultural Water Management, 290: 108587.
https://doi.org/10.1016/j.agwat.2023.108587

Xu H., Liu M., Tang Y., Zhao F., Cao W., He M., Peng D., and Dai X., 2023, Optimized management strategy increased grain yield, promoted nitrogen balance, and improved water productivity in winter wheat, Frontiers in Plant Science, 14: 1182568.
https://doi.org/10.3389/fpls.2023.1182568

Yang D., Cai T., Luo Y., and Wang Z., 2019, Optimizing plant density and nitrogen application to manipulate tiller growth and increase grain yield and nitrogen-use efficiency in winter wheat, PeerJ, 7: e6484.
https://doi.org/10.7717/peerj.6484

Zhang D., Wang H., Li D., Li H., Ju H., Li R., Batchelor W., and Li Y., 2019, DSSAT-CERES-Wheat model to optimize plant density and nitrogen best management practices, Nutrient Cycling in Agroecosystems, 114: 19-32.
https://doi.org/10.1007/s10705-019-09984-1

Zhang X.Q., Du S., Xu Y., Cao C., and Chen H., 2021, Reducing N application by increasing plant density based on evaluation of root, photosynthesis, Naccumulation and yield of wheat, Agronomy, 11(6): 1080.
https://doi.org/10.3390/AGRONOMY11061080

Zheng B., Jiang J., Wang L., Huang M., Zhou Q., Cai J., Wang X., Dai T., and Jiang D., 2022, Reducing nitrogen rate and increasing plant density accomplished high yields with satisfied grain quality of soft wheat via modifying the free amino acid supply and storage protein gene expression, Journal of Agricultural and Food Chemistry, 70(7): 2146-2159.
https://doi.org/10.1021/acs.jafc.1c07033

Zheng F., Qin J., Hua Y., Chu J., Dai X., and He M., 2023, Nitrogen uptake of winter wheat from different soil depths under a modified sowing pattern, Plant and Soil, 487: 533-546.
https://doi.org/10.1007/s11104-023-05952-5

Zhou W., Yan S., Rehman A., Li H., Zhang S., Yong Y., Liu Y., Xiao L., Zheng C., and Li W., 2024, Increasing planting density with reduced topdressing nitrogen inputs increased nitrogen use efficiency and improved grain quality while maintaining yields in weak-gluten wheat, Agriculture, 15(1): 13.
https://doi.org/10.3390/agriculture15010013