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Optimization of Sowing Density for Wheat Following Rice and Its Impact on Yield

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Abstract This study explores the optimization of sowing density for wheat after rice, evaluates its impact on wheat yield and growth performance, analyzes the key factors affecting sowing density, including soil conditions, climate factors, and variety characteristics after rice cultivation, compares the effects of high, low, and medium sowing density strategies on tillering, biomass accumulation, grain number and weight, and overall yield stability, and evaluates the actual effects of different sowing densities through case studies. Processing and observation provide valuable insights into the optimal density range, emphasizing the benefits of medium density planting, balanced resource efficiency, and maximizing yield. This study contributes to sustainable reinforcement work and provides practical recommendations for future research and policy-making.

Keywords Wheat-rice cropping system; Sowing density; Yield optimization; Post-rice wheat; Precision agriculture

1 Introduction

Wheat-rice cropping systems are a prevalent agricultural practice, particularly in regions such as the middle and lower reaches of the Yangtze River in China and the Indo-Gangetic Plains, where they form a crucial part of the double-cropping system. This system involves the sequential cultivation of rice and wheat on the same land within a single year, maximizing land use and productivity. However, the continuous cultivation of these crops poses challenges, such as soil degradation and nutrient depletion, which can affect subsequent wheat yields (Roy et al., 2024). The physical and chemical constraints imposed by rice paddies, such as increased soil bulk density and reduced nitrogen availability, are significant factors that can inhibit wheat growth and yield (Yang et al., 2022).

Sowing density is a critical factor in wheat cultivation, influencing plant growth, yield, and resource use efficiency. Optimal sowing density can enhance canopy structure, improve microenvironment conditions, and maximize yield potential by balancing the number of spikes per unit area and grain weight (Chen et al., 2022; Zhang et al., 2023a). However, excessive planting density can lead to issues such as increased lodging risk and reduced grain quality due to competition for resources (Feng et al., 2024; Mu et al., 2024). Therefore, determining the optimal sowing density is essential for achieving high yields and maintaining grain quality, especially in systems where wheat follows rice cultivation (Zheng et al., 2022).

This study reviews the optimization of wheat sowing density after rice planting, evaluates its impact on yield and quality, and explores the relationship between sowing density, canopy structure, and yield composition. By evaluating different sowing densities and their effects on wheat growth parameters, this study aims to provide insights into the best practices for managing wheat rice planting systems and provide recommendations for improving wheat productivity in rice wheat rotation systems.

2 Factors Influencing Sowing Density in Wheat Following Rice

2.1 Soil conditions post-rice harvest

The soil conditions following rice cultivation significantly impact the sowing density of wheat. Rice paddies often lead to increased soil bulk density and reduced availability of nitrogen, which can inhibit the growth and yield of subsequent wheat crops (Wang et al., 2022). This is due to the physical and chemical constraints imposed by the previous rice cultivation, such as higher soil bulk density and lower soil available nitrogen and organic matter compared to dryland wheat rotations (Table 1). Additionally, the soil's water retention capacity and porosity are altered, affecting root development and nutrient uptake in wheat (Pobereżny et al., 2023).

Table 1 Analysis of variance (ANOVA) of available N (AN), available P (AP), available K (AK), pH and organic matter (SOM) as affected by crop rotation and N treatment during wheat growing (anthesis) and after wheat harvest (Adopted from Yang et al., 2022)

Index	Crop rotation		N treatment		Crop rotation x N treatment	
	F	*P*-value	*F*	*P*-value	*F*	*P*-value
Anthesis						
AN	33.23	<0.000 1	0.5	0.734 2	1.52	0.235 3
AP	231.81	<0.000 1	4.6	0.008 5	7.6	0.000 7
AK	10.54	0.004	1.47	0.247 3	6.12	0.002 2
pH	8.94	0.007 2	0.83	0.522 4	1.38	0.275 5
SOM	46.42	<0.000 1	2.48	0.076 9	14.37	<0.000 1
Harvest						
AN	50.6	<0.000 1	18.46	<0.000 1	7.62	0.000 7
AP	286.85	<0.000 1	2.81	0.053 1	10.52	<0.000 1
AK	30.5	<0.000 1	3.45	0.026 8	14.02	<0.000 1
pH	25.66	<0.000 1	22.33	<0.000 1	2.89	0.048 9
SOM	24.09	<0.000 1	1.55	0.225 3	3.04	0.041 6

2.2 Climatic and seasonal considerations

Climatic and seasonal factors play a crucial role in determining the optimal sowing density for wheat following rice. In the Hangjiahu Plain of Zhejiang in China, the optimal sowing time for high-yield wheat is from late October to early November. However, the harvest time for rice is in mid to late November, which affects wheat sowing. Therefore, as the sowing time for wheat is delayed, the tillering of wheat will decrease and the density will decrease. In order to ensure higher yields, it is necessary to increase the sowing amount of wheat. Generally, from late October to early November, the standard sowing amount per hectare is 150 kilograms. When sowing is postponed to mid November, the sowing amount per hectare increases to 225 kilograms. When sowing is postponed to early December, the sowing amount per hectare increases to over 300 kilograms.In regions like the Indo-Gangetic Plains, climate change has led to increased temperatures and uneven rainfall, which can delay rice harvesting and subsequently affect the sowing of wheat (Roy et al., 2024). The timing of sowing is critical, as high temperatures during the grain-filling period can significantly reduce wheat yield (Chaplygin et al., 2023). Moreover, the microclimate within the wheat canopy, influenced by planting density, affects the crop's growth and development, with optimal densities helping to maintain favorable conditions for yield maximization.

2.3 Wheat varietal characteristics

The choice of wheat variety is another important factor influencing sowing density. Zhehua No.1 is strong tillering ability, shorter plant height, and strong lodging resistance, it can be planted at a higher density than other varieties (Zhang et al., 2024) .The more spikes achieve higher yield (Figure 1).Different wheat cultivars respond variably to sowing densities, with some varieties performing better under specific density conditions (Porker et al., 2018). For instance, certain cultivars have shown higher growth, yield, and quality parameters when sown at optimal densities, which can vary based on environmental conditions and genetic characteristics (Marinho et al., 2021). The physiological traits of the wheat variety, such as seed vigor and growth rate, also determine how well the plants can establish and thrive at different sowing densities (Zhou et al., 2019).

3 Optimal Sowing Density for Wheat Following Rice

3.1 High-density planting

High-density planting can significantly impact wheat yield, particularly in systems following rice cultivation. Studies have shown that increasing planting density can lead to a reduction in the leaf area index and a decrease in the number of grains per spike, which can negatively affect yield components such as thousand-grain weight. However, high-density planting can also improve yield by increasing the number of spikes per unit area, as seen in experiments with belt uniform sowing patterns (Chen et al., 2022). In some cases, increasing planting density by 40% has been shown to improve yield by enhancing grain filling, particularly in double-cropping systems (Zhou et al., 2023).

Figure 1 Performance of Zhehua No.1 wheat variety during seedling and maturity stages (Photo by Huazhong Shen)
Image caption: a: more tillers during the seedling stage; b: more spikes during maturity period (Photo by Huazhong Shen)

3.2 Low-density planting

Low-density planting, while potentially reducing competition for resources among plants, may not always lead to optimal yields. For instance, study of Marinho et al. (2022) found that lower sowing densities resulted in reduced seed yield and physiological quality, particularly under varying environmental conditions. Additionally, low-density planting can lead to less efficient use of available resources, such as water and nutrients, which can be critical in rice-wheat rotation systems where soil conditions are already challenging (Yang et al., 2022).

3.3 Moderate-density planting (optimal range)

Moderate-density planting often represents the optimal range for balancing resource use and maximizing yield. Research indicates that a sowing density of around 3.15 million plants per hectare can achieve high grain yield and economic efficiency in late-sown wheat under rice stubble (Yang et al., 2013). Similarly, moderate densities have been associated with improved canopy structure and microenvironment, which are crucial for maximizing yield potential. In different environments, a density of 350 seeds per square meter has been found to provide a suitable economic yield without compromising seed quality. This suggests that moderate-density planting can optimize the trade-offs between plant competition and resource availability, leading to better overall performance in wheat following rice.

4 Yield and Growth Impacts of Sowing Density

4.1 Influence on tillering and biomass accumulation

Sowing density significantly influences tillering and biomass accumulation in wheat. Higher sowing densities tend to reduce the leaf area index in the lower and middle parts of the canopy, which can affect the microenvironment and overall plant growth. Additionally, increased sowing density can lead to higher shoot dry matter accumulation, particularly when using belt uniform sowing patterns, which enhances biomass partitioning to the spike. However, excessive density may also lead to competition for resources, potentially reducing individual plant growth and tillering (Bai et al., 2016).

4.2 Grain number and weight

The number of grains per spike and the thousand-grain weight are crucial yield components affected by sowing density. Study of Zhang et al. (2023a) has shown that as sowing density increases, both the number of grains per spike and the thousand-grain weight tend to decrease. This is due to increased competition among plants for nutrients and light, which can limit the resources available for grain development. However, optimal sowing densities can maximize yield by balancing the number of spikes and grain weight, as demonstrated in experiments with different wheat varieties (Chen et al., 2022).

4.3 Harvest index and yield stability

The harvest index, which is the ratio of grain yield to total above-ground biomass, is an important indicator of yield stability. Sowing density can influence the harvest index by affecting the distribution of biomass between vegetative and reproductive parts. While higher densities can increase the number of spikes, they may also reduce grain weight, potentially affecting the harvest index. Yield stability is also influenced by the ability of the crop to maintain productivity under varying environmental conditions, which can be optimized by adjusting sowing density to suit specific climatic and soil conditions (Slatni et al., 2023).

5 Case Study

5.1 Background of the case study

The rice-wheat cropping system is a prevalent agricultural practice in many regions, including the Indo-Gangetic Plains and parts of China. This system often faces challenges such as soil degradation and reduced wheat yields following rice cultivation due to physical and chemical soil constraints (Yang et al., 2022). The optimization of sowing density for wheat following rice is crucial to enhance yield and economic efficiency, especially under varying environmental conditions and management practices.

5.2 Sowing density

Sowing density plays a significant role in determining the yield and quality of wheat crops. Studies have shown that different sowing densities can affect the canopy structure, microenvironment, and ultimately the yield of wheat (Figure 2). For instance, optimal sowing densities for maximizing yield have been identified as 278×10^4 plants/ha for large-spike varieties and 156×10^4 plants·ha^{-1} for multi-spike varieties (Zhang et al., 2023a). Additionally, a sowing density of 3.15 million plants per hectare has been found to optimize grain yield and economic efficiency in late-sown wheat under a rice-wheat cropping system.

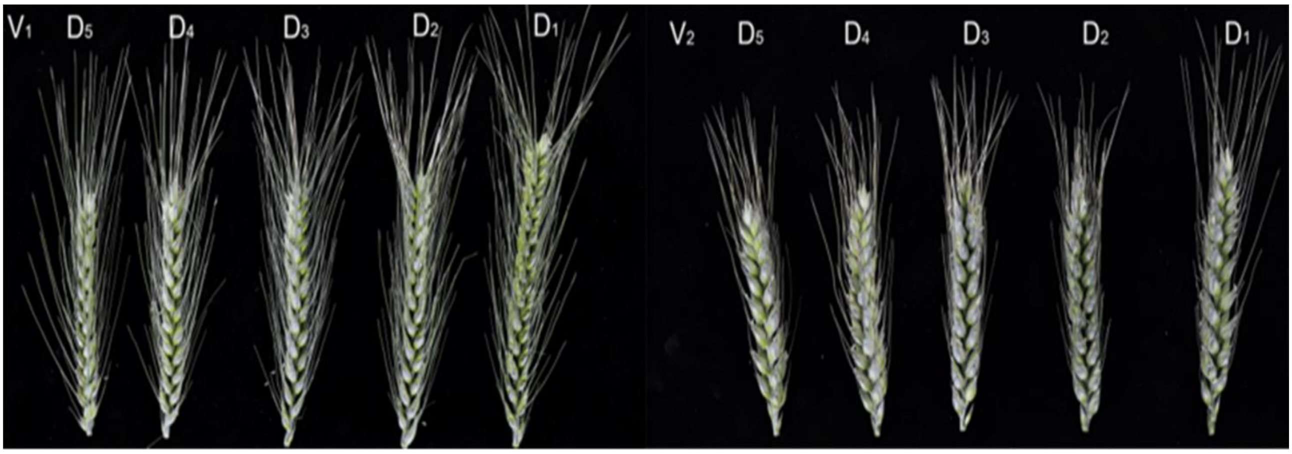

Figure 2 Effects of planting density on the spikes of uniformly sown winter wheat. V1, Xindong 50. V2, Sangtamu 4. D1-D5 refer to 123×10^4, 156×10^4, 204×10^4, 278×10^4, and 400×10^4 plants·ha^{-1} planting densities, respectively (Adopted from Zhang et al., 2023a)

5.3 Key findings and practical implications

This study highlights several key findings regarding the impact of sowing density on wheat yield following rice cultivation. Increased sowing density can lead to improved yield by optimizing the canopy structure and microenvironment, which are crucial for crop growth and development. However, it is also important to balance sowing density with other factors such as nitrogen fertilization to achieve the best economic outcomes (Marinho et al., 2022). The findings suggest that adopting optimal sowing densities can significantly enhance wheat yield and economic returns in rice-wheat cropping systems. This has practical implications for farmers aiming to improve productivity and sustainability in these systems, particularly in regions facing soil and climate challenges (Bai et al., 2016).

6 Challenges and Limitations in Sowing Density Optimization

6.1 Environmental and climatic variability

Environmental and climatic variability significantly impact the optimization of sowing density for wheat following rice. Variations in temperature, rainfall, and soil conditions can lead to inconsistent wheat yields. For instance, in the Indo-Gangetic Plains, delayed sowing due to climatic changes such as increased temperatures and uneven rainfall can adversely affect wheat yield and quality. Similarly, in rain-fed wheat systems, environmental factors like terminal drought and frost complicate the determination of optimal sowing density, as these conditions affect the water regime and, consequently, the yield (Tokatlidis, 2014). The unpredictability of weather patterns makes it challenging to establish a consistent sowing density that maximizes yield across different seasons and locations (Vitantonio-Mazzini et al., 2020).

6.2 Resource constraints and soil health

Resource constraints, including water and nitrogen availability, are critical limitations in optimizing sowing density. In rice-wheat rotations, the physical and chemical constraints of soil, such as increased bulk density and reduced nitrogen availability following rice paddies, can inhibit wheat growth and yield (Xu et al., 2023). Additionally, optimizing nitrogen use efficiency (NUE) is crucial, as excessive nitrogen inputs can lead to environmental issues like increased nitrous oxide emissions, while insufficient nitrogen can result in yield gaps (Bai and Tao, 2017; Zhang et al., 2023b). Soil health, including organic matter content and nutrient availability, plays a vital role in determining the success of sowing density optimization.

6.3 Farmer adoption and knowledge gaps

Farmer adoption of optimized sowing density practices is often hindered by knowledge gaps and risk aversion. Many farmers lack access to the latest research and technologies that could help them optimize sowing density for better yields. In Bangladesh, for example, farmers' low risk-bearing capacity and limited investment in new practices contribute to suboptimal sowing densities and yield outcomes (Krupnik et al., 2015). Additionally, understanding the reasons behind farmers' reluctance to adopt higher nitrogen rates or adjust sowing dates is essential for bridging yield gaps (Khaliq et al., 2019). Educating farmers on the benefits of optimized sowing density and providing them with the necessary resources and support can enhance adoption rates and improve overall productivity.

7 Future Directions in Wheat Sowing Density Optimization

7.1 Precision agriculture and data-driven approaches

The integration of precision agriculture and data-driven approaches offers promising avenues for optimizing wheat sowing density (Wu, 2024). By utilizing advanced technologies such as remote sensing, GPS, and data analytics, farmers can tailor sowing densities to specific field conditions, thereby enhancing yield potential. For instance, precision agriculture can help in monitoring canopy structure and microenvironmental conditions, which are crucial for maximizing yield as demonstrated in studies on canopy structure and planting density (Zhang et al., 2023a). Additionally, data-driven models can predict optimal sowing densities by analyzing historical yield data and environmental variables, thus enabling more informed decision-making.

7.2 Breeding for density-tolerant wheat varieties

Breeding programs focused on developing wheat varieties that can thrive under varying sowing densities are essential for future agricultural sustainability. Research has shown that different wheat genotypes respond uniquely to sowing densities, affecting yield and physiological quality (Marinho et al., 2022). By selecting and breeding for traits that enhance density tolerance, such as improved root systems and efficient nutrient uptake, it is possible to develop varieties that maintain high yields even at higher planting densities (Huang et al., 2024). This approach not only maximizes land use efficiency but also supports the adaptation to changing climatic conditions (Yang et al., 2022).

7.3 Sustainable intensification and policy support

Sustainable intensification, which aims to increase agricultural productivity while minimizing environmental impact, is a critical future direction for optimizing wheat sowing density. Practices such as zero-tillage and the use of Turbo Happy Seeder have been shown to improve yield and reduce costs in rice-wheat systems (Kumar et al., 2024). Policy support is crucial in promoting these sustainable practices, providing incentives for farmers to adopt new technologies and methods. Additionally, policies that support research and development in agronomic management and modern cultivars can further enhance yield outcomes in rice-wheat rotation systems. By aligning policy frameworks with sustainable agricultural practices, it is possible to achieve higher productivity and environmental conservation simultaneously.

8 Conclusion

The optimization of sowing density for wheat following rice has significant implications for yield outcomes. Studies have shown that the choice of sowing density can influence various factors such as canopy structure, microenvironment, and yield components. For instance, optimal planting densities were found to maximize yields by improving canopy structure and microenvironment conditions, as demonstrated in experiments with different wheat varieties. Additionally, the combination of sowing density with nitrogen fertilization has been shown to affect both yield and economic efficiency, with specific density and nitrogen combinations yielding the highest results. Furthermore, the physical and chemical constraints imposed by preceding rice paddies can impact subsequent wheat yields, highlighting the importance of managing soil conditions effectively.

The findings underscore the importance of optimizing sowing density as a strategy for enhancing agricultural sustainability. By adjusting planting densities, farmers can improve water use efficiency and soil health, which are critical for sustainable farming practices. Moreover, the integration of optimal sowing densities with reduced nitrogen application can lead to improved grain filling and yield, contributing to more sustainable crop production systems. These practices not only enhance yield but also reduce input costs and environmental impact, aligning with sustainable agriculture goals.

Future research should focus on exploring the interactions between sowing density, soil health, and environmental conditions to develop more comprehensive guidelines for farmers. Studies could investigate the long-term effects of different sowing densities on soil properties and crop rotation systems, particularly in diverse climatic regions. Additionally, research should aim to refine the balance between sowing density and nitrogen application to optimize both yield and environmental outcomes. Practically, farmers are encouraged to adopt precision agriculture techniques to tailor sowing densities and input applications to specific field conditions, thereby maximizing yield potential and sustainability.

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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.

References

Bai H., and Tao F., 2017, Sustainable intensification options to improve yield potential and eco-efficiency for rice-wheat rotation system in China, Field Crops Research, 211: 89-105.
https://doi.org/10.1016/J.FCR.2017.06.010

Bai H., Tao F., Xiao D., Liu F., and Zhang H., 2016, Attribution of yield change for rice-wheat rotation system in China to climate change, cultivars and agronomic management in the past three decades, Climatic Change, 135: 539-553.
https://doi.org/10.1007/s10584-015-1579-8

Chaplygin M., Zhalnin E., Shibryaeva L., and Podzorov A., 2023, Patterns of influence of winter wheat sowing density on its yield, Engineering Technologies and Systems, 33(4): 490-507.
https://doi.org/10.15507/2658-4123.033.202304.490-507

Chen M., Zhu Y., Ren M., Jiang L., He J., and Dong R., 2022, Does belt uniform sowing improve winter wheat yield under high sowing density? Agronomy, 12(12): 2936.
https://doi.org/10.3390/agronomy12122936

Feng S., Shi C., Wang P., Chang S., Liu C., Shen C., Li S., Hu T., and Ru Z., 2024, Optimizing wheat planting density by adjusting population structure and stabilizing stem strength to achieve high and stable yields, Agronomy, 14(8): 1853.
https://doi.org/10.3390/agronomy14081853

Huang F., Du X.Y., Zou S.K., Wang L., and Han Y.L., 2024, Advancements in wheat hybridization: overcoming biological barriers, Bioscience Evidence, 14(5): 195-205.
https://doi.org/10.5376/be.2024.14.0021

Khaliq T., Gaydon D., Ahmad M., Cheema M., and Gull U., 2019, Analyzing crop yield gaps and their causes using cropping systems modelling-a case study of the Punjab rice-wheat system, Pakistan, Field Crops Research, 232: 119-130.
https://doi.org/10.1016/J.FCR.2018.12.010

Krupnik T., Ahmed Z., Timsina J., Shahjahan M., Kurishi A., Miah A., Rahman B., Gathala M., and McDonald A., 2015, Forgoing the fallow in Bangladesh's stress-prone coastal deltaic environments: effect of sowing date, nitrogen, and genotype on wheat yield in farmers' fields, Field Crops Research, 170: 7-20.
https://doi.org/10.1016/J.FCR.2014.09.019

Kumar S., Shivani Kumar S., Mondal S., Singh S., and Singh K., 2024, Economics and yield response in rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system as influenced by different tillage and sowing methods in Eastern Region, Indian Journal of Agronomy, 62(4): 394-400.
https://doi.org/10.59797/ija.v62i4.5535

Marinho J., Silva S., De Souza D., Fonseca I., Bazzo J., and Zucareli C., 2021, Wheat yield and seed physiological quality affected by initial seed vigor, sowing density, and environmental conditions, Semina: Ciências Agrárias, 42: 1595-1614.
https://doi.org/10.5433/1679-0359.2021v42n3supl1p1595

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

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

Pobereżny J., Wszelaczyńska E., Lamparski R., Lemanowicz J., Bartkowiak A., Szczepanek M., and Gościnna K., 2023, The impact of spring wheat species and sowing density on soil biochemical properties, content of secondary plant metabolites and the presence of *Oulema* ssp., PeerJ, 11: e14916.
https://doi.org/10.7717/peerj.14916

Porker K., Straight M., and Hunt J., 2018, Evaluation of G×E×M interactions to increase harvest index and yield of early sown wheat, Frontiers in Plant Science, 11: 994.
https://doi.org/10.3389/fpls.2020.00994

Roy D., Vashisth A., Krishnan P., Mukherjee J., Meena M., Biswakarma N., Rathore P., Bag K., and Kumari S., 2024, Delayed sowing and its ramifications: biophysical, yield, and quality analysis of wheat cultivars in the north-west Indo-Gangetic plains, Journal of the Science of Food and Agriculture, 104(11): 6831-6843.
https://doi.org/10.1002/jsfa.13512

Slatni A., Yacoubi S., Hermassi T., Latrech B., and Zayani K., 2023, Assessment of sowing density impact on water front advancement and infiltration in furrow irrigation, Agronomy, 13(8): 2080.
https://doi.org/10.3390/agronomy13082080

Tokatlidis I., 2014, Addressing the yield by density interaction is a prerequisite to bridge the yield gap of rain-fed wheat, Annals of Applied Biology, 165(1): 27-42.
https://doi.org/10.1111/AAB.12121

Vitantonio-Mazzini L., Borrás L., Garibaldi L., Pérez D., Gallo S., and Gambin B., 2020, Management options for reducing maize yield gaps in contrasting sowing dates, Field Crops Research, 251: 107779.
https://doi.org/10.1016/j.fcr.2020.107779

Wang W., Shen C., Xu Q., Zafar S., Du B., and Xing D., 2022, Grain yield, nitrogen use efficiency and antioxidant enzymes of rice under different fertilizer N inputs and planting density, Agronomy, 12(2): 430.
https://doi.org/10.3390/agronomy12020430

Wu W.C., 2024, Predicting wheat response to drought using machine learning algorithms, Plant Gene and Trait, 15(1): 1-7.
http://dx.doi.org/10.5376/pgt.2024.15.0001

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 J.F., Ding J.F., Gu H.W., Zi Y., Zhu X.K., Peng Y.X., and Guo W.S., 2013, Effects of the combination of density and nitrogen fertilizer on grain yield and economic efficiency of late-sown wheat under rice stubble, Journal of Triticeae Crops, 33(3): 503-506.

Yang R., Wang Z., Fahad S., Geng S., Zhang C., Harrison M., Adnan M., Saud S., Zhou M., Liu K., and Wang X., 2022, Rice paddies reduce subsequent yields of wheat due to physical and chemical soil constraints, Frontiers in Plant Science, 13: 959784.
https://doi.org/10.3389/fpls.2022.959784

Zhang B.C., Zhu J.H., Fan M., and Hua W., 2024, Suitable nitrogen fertilization mode of wheat cultivar Zhehua No.1 under rice stubble and wheat planting mode, Barley and Cereal Sciences, 41(5): 49-53.
https://doi.org/10.14069/j.cnki.32-1769/s.2024.05.008

Zhang F., Zhang D., Li L., Zhang Z., Liang X., Wen Q., Chen G., Wu Q., and Zhai Y., 2023a, Effect of planting density on canopy structure, microenvironment, and yields of uniformly sown winter wheat. Agronomy, 13(3): 870.
https://doi.org/10.3390/agronomy13030870

Zhang X., Liu M., Zheng F., Dong Y., Hua Y., Chu J., He M., and Dai X., 2023b, Optimizing sowing patterns in winter wheat can reduce N_2O emissions and improve grain yield and NUE by enhancing N uptake, Frontiers in Plant Science, 14: 1176293.
https://doi.org/10.3389/fpls.2023.1176293

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

Zhou C., Huang Y., Jia B., Wang S., Dou F., Samonte S., Chen K., and Wang Y., 2019, Optimization of nitrogen rate and planting density for improving the grain yield of different rice genotypes in Northeast China, Agronomy, 9(9): 555.
https://doi.org/10.3390/agronomy9090555

Zhou W., Yan L., Fu Z., Guo H., Zhang W., Liu W., Ye Y., and Long P., 2023, Increasing planting density and reducing n application improves yield and grain filling at two sowing dates in double-cropping rice systems, Plants, 12(12): 2298.
https://doi.org/10.3390/plants12122298