Front. Agr. Sci. Eng. 2025, 12(3): 530–544 https://doi.org/10.15302/J-FASE-2025636

REVIEW

Integrated innovation and application of green high-yield and high-efficiency technologies of rice in China

Jian HUANG, Yixiao CHAI, Shichao YANG, Yiwen CAO, Lei YANG, Min WANG, Xusheng MENG (✉), Shiwei GUO

Jiangsu Provincial Key Lab for Organic Solid Waste Utilization, National Engineering Research Center for Organic-based Fertilizers, Jiangsu Collaborative Innovation Center for Solid Organic Waste Resource Utilization, Nanjing Agricultural University, Nanjing 211800, China.

KEYWORDS

Rice, yield, nitrogen use efficiency, soil fertility, sustainable production

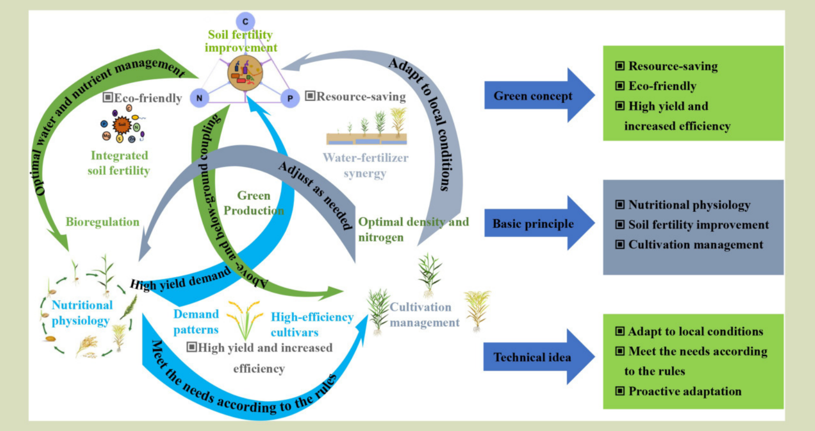
HIGHLIGHTS

- Excessive fertilizer application and inefficient water management limit rice productivity and sustainability in China.
- Optimize nutrient management and crop production methods based on nutritional and physiological basis of rice yield formation.
- Innovative products and technologies improve rice water and fertilizer use efficiency and promote green rice production.
- Ideas for green and sustainable development of rice in China are proposed.

Received May 8, 2025;
Accepted May 31, 2025.

Correspondence: T2023162@njau.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

China’s high rice yield is primarily achieved through intensive fertilizer application and substantial water resource consumption, which has resulted in significant environmental risks. There is an urgent need to develop innovative green technologies that simultaneously ensure high yield and production efficiency to achieve sustainable rice production. This paper systematically analyzes both nationwide challenges and region-specific constraints affecting rice production. The proposed solutions focus on three key innovations: constructing high-yield populations, coupling aboveground and belowground, and improving soil fertility. Implementation of these green high-yield and high-efficiency technologies demonstrates potential to maintain or increase yields while achieving three critical improvements: enhanced nitrogen use efficiency, reduced irrigation water consumption and decreased greenhouse gas emissions. To facilitate large-scale adoption, priority should be given to developing rice-related products, integrating rice-upland rotating system and establishing localized implementation models based on these technological innovations.

1 Introduction

Rice (*Oryza sativa*) is pivotal for global food security, providing sustenance for over half of China's population[1]. However, rice production needs to increase annually by 1% to meet the growing demands[2]. Over the past 50 years, several rice breeding programs have been conducted to improve rice yield potential. It is well documented that the newly bred hybrid rice cultivars demonstrate a 9%–20% yield gain compared to inbred rice cultivars[3,4]. The optimization of genetic variations, along with improved agronomic management and increased input of agricultural chemicals, have been crucial for enhancing rice yield[5]. Nitrogen fertilizer input is a key factor in rice production, determining biomass accumulation[6]. Meanwhile, rice production accounts for 16% of global N fertilizer consumption[7], resulting in overuse and declining nitrogen use efficiency (NUE)[8]. China accounts for about 20% of global rice production area but uses 37% of global N fertilizer for rice production[9], highlighting that yield increases depend heavily on N application. Although China's rice yield per unit area exceeds the global average[10], its partial factor productivity of N is below the average for all continents[11]. Excessive N use has emerged as a critical issue. Nitrogen exists in various forms within soil and is lost through runoff, leaching, volatilization and denitrification[12]. Therefore, excessive N application can lead to soil degradation as well as air and water pollution. Rice production accounts for about 48% of farmland greenhouse gases, with Chinese paddies releasing 712 Mt CO_2 eqv, higher than other major rice-producing countries[13]. The N application rate is considered as the primary driver of N_2O emission, as excessive N accelerates nitrification and denitrification while lowering soil pH[14,15]. Urgent innovation in rice production is needed to address these challenges.

Crop yield depends on biomass and harvest index at maturity, with increasing biomass being regarded as an important strategy to enhance yield[16]. Biomass accumulation relies on radiation interception by the canopy and radiation use efficiency (RUE)[17]. Optimizing photosynthesis is considered as a key strategy to improve RUE[18]. Most N in plants accumulates in leaves, with about 75% allocated to the photosynthetic apparatus[19,20]. A strong positive correlation exists between leaf photosynthetic rate and N content[21,22]. Photosynthetic nitrogen use efficiency, defined as the ratio of leaf photosynthetic rate to N content[20], demonstrates a significant positive correlation with nitrogen utilization efficiency (NUtE)[23,24]. NUE is determined by both N uptake efficiency and NUtE[25]. Optimizing NUtE through rational N fertilizer application contributes to maximizing crop productivity while reducing fertilizer inputs[26,27]. This approach provides a theoretical foundation for achieving high-yield and high-efficiency rice production.

From 2005 to 2015, the application of green high-yield and high-efficiency technologies, based on locally applicable recommendations developed through large-scale field trials, increased average yields of maize, rice and wheat by 10.8%–11.5%[28]. Additionally, N application of these crops decreased by 14.7%–18.1%, leading to a reduction of calculated reactive N losses by 22.9%–34.9% and a decline in greenhouse gas emissions by 18.6%–29.1%. These results demonstrate that green high-yield and high-efficiency technologies can achieve both crop yield increases and large-scale environmental emission reductions. However, due to the vast geographic distribution of rice-growing regions in China, significant variation exists in soil nutrient status and climatic conditions (e.g., temperature, rainfall and solar radiation). Therefore, region-specific adaptation of these technologies is essential to align with local rice production contexts. Translating such technologies into practical solutions for farmers remains a challenge in agricultural production. To address this, Science and Technology Backyard programs have been established to foster collaboration among government agencies, agricultural enterprises, universities and farmers, bridging the gap between research innovations and on-field implementation[29,30]. In the 2010s, policy-driven initiatives, such as crop straw return and organic fertilizer application, improved China's soil fertility, with indicators like soil organic matter and available potassium showing significant increases[31–33]. Thus, the synergy of scientific techniques, farmer engagement and policy incentives are critical to unlocking the full potential of green high-yield and high-efficiency rice production in China.

Leveraging the research findings from nationwide rice science and technology backyard, this study first systematically analyzes the key constraints and regional disparities in rice production across China. From this analysis, we propose innovative strategies for enhancing green production efficiency, with a focus on the physiologic and nutritional mechanisms underlying rice yield formation, paddy soil fertility dynamics and optimized crop production practices. We then quantitatively evaluate the impacts of core technologies on yield improvement and resource use efficiency. Finally, we establish an implementation framework integrating model development, localized adaptation and scalable dissemination of green high-efficiency production systems.

2 Key issues and limiting factors of regional production

China has five major rice production regions, including the single and double cropping rice regions in South China, the single and double cropping rice regions in the Yangtze River Basin, the single cropping rice region in the mountainous areas of Southwest China, the early maturing single cropping rice region in Northeast China, and the single cropping rice region in the dry areas of Northwest China. Based on the practical conditions of rice production in China's five major producing regions, the critical constraints on rice production in China demonstrate characteristics of both national universality and regional specificity.

2.1 Nationwide common problems

2.1.1 Suboptimal seedling management

Seedling quality critically determines rice yield and quality, with age-appropriate seedlings being pivotal for mechanized transplanting success. However, prevalent issues such as improper seeding rates, low-quality substrates and unscientific farmer practices frequently result in overaged seedlings, poor vigor and suboptimal population establishment. These deficiencies directly compromise yield potential and resource use efficiency[34–37].

2.1.2 Inefficient water management

While traditional flooding practices enhance initial nutrient availability, persistent waterlogging reduces soil redox potential, promotes accumulation of phytotoxic reductants (Fe^{2+}, Mn^{2+}, sulfides), and causes rhizosphere oxygen deprivation, collectively suppressing root metabolic activity and plant growth. Labor shortages and irrigation inefficiencies exacerbate these issues, limiting the adoption of dry-wet alternation strategies that enhance soil aeration and root development[38,39].

2.1.3 Limited dissemination of elite cultivars

Since the 1950s, about 3000 rice cultivars with an annual planting area of over 6.67 kha have been released in China, comprising about 80% inbred cultivars and 20% hybrid cultivars[40,41]. Although previous studies have reported that hybrid rice cultivars exhibit about 10% higher average grain yield compared to inbred cultivars, the production area of hybrid rice in China has shown a consistent decline in recent years[42]. Also, while the number of officially registered rice cultivars in China continues to increase rapidly, the number and area of major cultivars and dominant cultivars in China have decreased significantly, resulting in decreased concentration of rice cultivars[43].

2.1.4 Inefficient planting density

Planting density critically influences high-yield population establishment, photosynthetic efficiency and tillering regulation in rice[44–46]. In China, inappropriate sowing density remains prevalent in rice production, with excessive density causing poor canopy ventilation and light penetration, impaired ontogenesis and reduced RUE[47]. Conversely, low density promotes excessive individual plant growth[48], limiting effective panicles per unit area and hindering yield potential. Also, certain agricultural machinery designs have failed to adequately accommodate the production requirements across diverse rice production regions. For example, the row spacing and hill distance settings of rice transplanters often mismatch the optimal spacing parameters for local rice cultivars, resulting in poor population quality after transplantation. Compared to manually transplanted rice, mechanically transplanted fields frequently exhibit reduced panicle size[49].

2.1.5 Excessive fertilizer application

Despite the promotion of soil testing and formulated fertilizer application, excessive and unbalanced fertilizer application remains widespread. Many farmers apply excessive mineral fertilizers, aiming for high yields at the expense of NUE[50,51]. Excessive application of nitrogen and phosphorus leads to environmental degradation, including nutrient runoff, groundwater pollution and greenhouse gas emissions[52–54].

2.2 Regional-specific problems

2.2.1 Early-maturing single cropping region of Northeast China

The early-maturing single cropping rice zone in Northeast China frequently experiences low temperatures during the early growing season, which delays seedling greening and impairs tillering, ultimately reducing yield[55–57]. Also, intensive land reclamation in black soil areas has led to increased soil bulk density, reduced porosity, and decreased water retention, negatively affecting soil fertility and structure[58–61].

2.2.2 Single and double cropping region of the Yangtze River Basin

As China's largest rice-producing area, the Yangtze River Basin is vital for food security[62]. However, intensive tillage, shallow soil profiles and low organic matter restrict root development and yield potential[63]. Long-term flooding and excessive fertilizer application result in severe nitrogen and phosphorus runoff[52,64,65]. Simultaneously, light-temperature mismatch during key growth stages limits yield potential[66,67].

2.2.3 Double cropping region of South China

In the double cropping rice areas of South China, the abundance of water and heat resources supports intensive production. Nevertheless, excessive input of water and fertilizers has led to significant agricultural non-point source pollution and elevated greenhouse gas emissions[68].

2.2.4 Mountainous single cropping region of Southwest China

The complex terrain severely limits the application of standard farming machinery, making large-scale equipment unsuitable for steep, fragmented plots and resulting in low operational efficiency. Simultaneously, the region is frequently exposed to high temperatures during critical growth stages, particularly the grain-filling phase, where inconsistent thermal regimes directly impair yield potential[66].

2.2.5 Arid single cropping region of Northwest China

Rice production in the arid of Northwest China is constrained by limited water availability, high soil salinity and low accumulated temperatures[69]. These conditions hinder rice growth and limit yield stability. Also, flood irrigation, essential due to water scarcity, results in high nitrogen leaching and reduced NUE[53,54].

3 Innovative ideas of green production increase and efficiency technology

3.1 Nutritional and physiologic principles of rice yield formation

Excessive N fertilizer application, particularly during early growth stages, is a common practice in Chinese rice production, leading to an imbalance between N supply and crop demand[9,70]. Addressing this challenge requires integrating rice growth patterns with nutrient requirement dynamics (Fig. 1). Rice yield is determined by four components: panicle number per unit area, spikelets per panicle, 1000-grain weight and filled grain rate. Of these yield components, panicle density (panicles per unit area) has been identified as the primary yield-limiting factor[71]. Panicle density correlates positively with tiller formation during early growth stages, which is strongly influenced by N availability[72,73]. Consequently, N application at the tillering

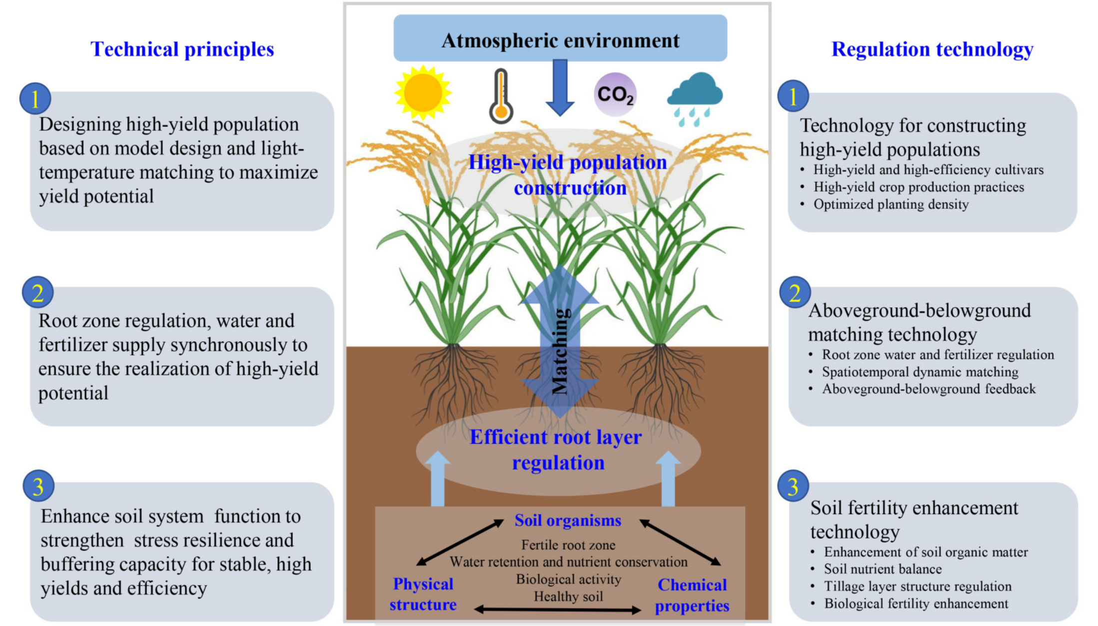


Fig. 1 Innovative ideas of green yield increase and efficiency improvement technologies for rice.

stage effectively promotes tiller development. However, excessive tillering may reduce yield through non-productive tiller abortion, decreased spikelet formation, and impaired grain filling[74]. Also, a negative correlation between spikelets per panicle and panicle density[75]. The plant N content during late spikelet differentiation critically regulates spikelet number per panicle[76]. Optimizing the distribution of N fertilizer application at different growth stages, by reducing base and tiller fertilizers while increasing N supply at the panicle initiation stage, contributes to balance spikelets per panicle and panicle density, thereby maximizing the number of spikelets per unit area.

Maintaining optimal photosynthetic rates represents a key determinant of high rice yields. Previous studies demonstrate that photosynthetic rate is regulated by leaf N content[77–79], with a demonstrated positive correlation observed between photosynthetic capacity and grain yield[80]. However, when N application exceeds critical thresholds, both leaf photosynthetic rate and rice yield cease to increase[81]. Under low N supply, plants promote the allocation of leaf N to photosynthetic processes[82], suggesting that moderate N supply can optimize N partitioning to sustain photosynthetic efficiency. The grain filling stage constitutes the critical phase for yield formation, requiring adequate nutrient supply to maintain photosynthesis and ensure assimilate transport from source to sink[83,84]. Therefore, increasing the application ratio of N fertilizer during grain filling improves synchronization between N supply and crop demand. Organic-mineral substitution emerges as an effective strategy to sustain rice N requirements[85]. An earlier study demonstrated that this approach enhances grain filling rates by prolonging source activity duration and balancing source-sink relationships[86].

3.2 Improvement of paddy soil fertility

Soil fertility refers to the capacity of a soil to sustain crop nutrient supply, which can be enhanced through appropriate agricultural practices including tillage, irrigation management and fertilizer application[14,87,88]. Conversely, inappropriate agricultural practices, such as excessive N application, imbalanced fertilizer application without organic fertilizer addition and post-harvest straw removal, accelerate land degradation while reducing agricultural productivity[89,90]. Across cropping systems, grain yield exhibits a positive correlation with integrated fertility quality index (IFQI), and IFQI improvement contributes to yield stability[91,92]. Typically, grain yield is positively correlated with the IFQI in various cropping systems. Also, improving the IFQI helps enhance crop yield stability[91]. Among different fertilizer treatments, organic amendments (e.g., farmyard manure or crop straw) demonstrate superior IFQI enhancement compared to mineral-only fertilizer application. Long-term organic fertilization significantly increases soil organic carbon (SOC) and total N while improving P and K availability[91]. SOC is pivotal for soil productivity, regulating soil physical properties and mitigating acidification rates[93]. Also, SOC accumulation enhances nutrient availability and reduces yield variability in agroecosystems[94].

Organic fertilizer application not only modifies soil physicochemical properties but also modulates microbial community dynamics[95]. Soil microbial communities are vital for soil organic matter accumulation and mineralization, while regulating enzyme activities, microbial biomass and community composition[96]. Also, these communities govern nutrient use efficiencies and mediate ecosystem resource equilibria[97]. Integrated organic-mineral fertilizer application stimulates microbial activity, enhancing organic matter decomposition and nutrient transformation[98,99], thereby improving soil fertility and stabilizing agricultural productivity.

Ammonia volatilization is an important pathway for N loss, with a loss rate of 17.2%[100]. Ammonia released into the atmosphere can easily be converted into nitrous pentoxide, nitrates and other nitrous oxides, which can polymerize to form aerosols and $PM_{2.5}$ particles, thereby polluting the atmospheric environment[101]. Additionally, N_2O, a potential greenhouse gas, has a warming potential 265 times greater than that of CO_2[102]. Therefore, it is necessary to explore reasonable fertilizer application practices in order to reduce NH_4 and N_2O emissions and contribute to the development of green agriculture. In the initial stage of rice growth, short plant stature combined with excessive basal N application limits nutrient uptake efficiency. Concurrently, elevated field temperatures under solar radiation accelerate urea hydrolysis via enhanced soil urease activity, promoting NH_4^+-N accumulation and subsequent volatilization[103]. Previous studies have demonstrated that the combined application of organic and mineral fertilizers can mitigate NH_3 emissions[104,105]. Therefore, reducing the supply of N fertilizer during the early growth stage of rice and substituting a portion with organic fertilizer can effectively mitigate N loss and greenhouse gas emissions, while simultaneously enhancing soil fertility. This approach represents a crucial technology for attaining environmentally sustainable and high-yield rice production.

3.3 Optimizing production management

Increasing N fertilizer input is considered as an important means of improving rice population productivity, but the effect of changes in planting density is often ignored. High N supply increases population productivity mainly by increasing tiller number, but it also leads to delayed maturation, ineffective tillering, plant lodging and reduced grain filling rates[106,107]. Earlier studies have shown that optimal increases in planting density can enhance biomass accumulation and leaf area index, thereby improving N absorption during the vegetative growth period[81,108]. Therefore, aligning planting density with N application rates enhances rice yield. Studies in Jiangsu Province demonstrate that adding about 1000 hills ha^{-1} reduces N requirement by 1 kg·ha^{-1}[81]. Under current production conditions, combining increased planting density with reduced N input achieves higher yields alongside enhanced NUE.

In addition to improving aboveground production management, deep tillage implementation is recommended. Deep tillage breaks up soil compaction layers and increases topsoil volume, while more critically enhancing soil porosity, water retention capacity, aeration efficiency and root system development[109–111]. Innovative techniques, such as side deep fertilizer placement, are increasingly adopted in rice production. This technique involves strip-application of fertilizer at 3–5 cm depth adjacent to seedlings (5–8 cm lateral distance), ensuring precise nutrient delivery to the root zone[112]. By concentrating fertilizers near roots, side deep fertilizer placement boosts nutrient absorption efficiency while reducing aquatic pollution from runoff[113,114]. Compared to standard fertilizer application methods, side deep fertilizer placement increases the nutrient concentration in the roots to meet the needs of rice growth. Machine-transplanted rice trials demonstrate that side deep fertilizer placement enhances photosynthetic rate, dry matter accumulation and grain yield[115]. From the perspective of nutrient balance, side deep fertilizer placement suppresses urease activity, enhances mineral N content in the deep soil layer, thereby reducing leaching losses[116]. Also, side deep fertilizer placement has the potential to modulate the composition and abundance of soil microorganisms, thereby enhancing soil fertility and providing a suitable growth environment for rice.

In China, more than 95% of rice is produced under irrigated conditions, with around 70% of agricultural irrigation water used for rice production[117,118]. Based on the fact that continuous flooding is not necessary for rice to achieve high yields, alternate wetting and drying (AWD) irrigation technology has been widely adopted in rice production[119,120]. In the AWD irrigation regime, once the transplanted seedlings are well established, the field water depth is allowed to fall to a threshold depth below the soil surface for a certain period before the next irrigation is applied[121]. Under continuous flooding conditions, paddies emit vast amounts of CH_4[122]. Therefore, the adoption of AWD technology conserves water while simultaneously mitigating greenhouse gas emissions[123].

4 Effects of green production increase and efficiency technology

Key technologies for optimized fertilizer application and crop production management are applied to address production constraints in different rice production regions based on their specific limiting factors. In South China, heavy rainfall and severe runoff lead to poor water and fertilizer retention in soils, while improper irrigation practices cause accumulation of soil reducing substances and premature aging of rice roots, contributing to plant lodging. During the tillering stage, the peak period for CH_4 emissions and nitrogen loss, water-saving and emission-reduction irrigation control technology has been implemented. Compared with the AWD irrigation method developed by the International Rice Research Institute, the modified AWD irrigation technology demonstrates comparable or slightly increased rice yields while achieving 19.0% reduction in irrigation water consumption, 16.2% decrease in CH_4 emissions, and 13.9% reduction in global warming potential[123,124]. In Northeast China, where low temperatures during early growth stages delay rice greening, the application of N-Zn co-application technology has proven effective. This approach combines ammonium nitrogen with urea nitrogen while supplementing Zn fertilizer during early growth phases, enhancing stress resistance and accelerating greening and growth processes[124]. The middle and lower reaches of the Yangtze River, as China’s primary rice-producing region, are impacted distinct climate-related challenges. In drought-flood rotation areas, tight crop schedules create production pressures. For double-cropping rice systems, suboptimal allocation of light and thermal resources between early and late rice cultivars remain problematic. In mixed single/double-cropping areas, single-crop systems underutilize available light and thermal resources while double-cropping systems experience scheduling stress. Recommended solutions include cultivating climate-adapted cultivars and adjusting sowing dates according to growth cycles.

Meanwhile, the present and earlier studies demonstrate that optimized nutrient management and production patterns can significantly enhance rice productivity. In Jiangsu Province, combining optimal nutrient management with organic-mineral fertilizer integration increased yields by 6.3% compared to standard farming practices[125]. Side deep fertilizer placement techniques have shown particular promise, boosting yields by about 10% while improving N agronomic efficiency by 8.1%–21.3%[126]. In the rice-growing areas of Northeast China, combining optimized nutrient management with increased planting density can achieve a yield increase of 9.8%[127]. In the rice-growing areas of South China, low-carbon and high-yield crop production can achieve a yield increase of 11.0%[128]. In the arid regions of Northwest China, optimizing irrigation and N fertilizer management strategies can achieve the maximum yield in areas with scarce water resources and limited soil N content[129]. In the rice-growing areas of Southwest China, combining optimized nutrient management with increased planting density can achieve a yield increase of 15.7%[130].

5 Regional green production and efficiency model integration

To ensure national food security, we propose integrating a national model to enhance rice yield and production efficiency, aiming to address key challenges in rice production while achieving sustainable improvements in productivity and resource utilization (Fig. 2). Firstly, the core issue stems from the inherent contradiction in seasonal resource allocation, where the synchronization of light, temperature, water and other critical resources required at successive rice growth stages cannot be fully optimized. This mismatch significantly impedes rice growth and development[55,131]. Secondly, China's major rice-producing regions have substantial geographical diversity, with variations in cultivated land quality and limited water-fertilizer retention capacity in specific areas. These constraints reduce the ability of soil to consistently supply adequate nutrients for rice production[132]. Thirdly, the occurrence of extreme climatic events in recent years, such as floods and droughts, has led to unstable water resource availability, exacerbating reliance on traditional irrigation and fertilizer application practices. This results in low efficiency in water and fertilizer use[133]. Finally, rice production management technologies remain outdated, lacking scientific and standardized operational procedures.

To address these challenges, we propose three fundamental technologies and corresponding strategies: (1) the integration of high-yield rice populations with highly efficient root systems, (2) optimization of water management and fertilizer application practices, and (3) enhancement of soil fertility through carbon sequestration and nitrogen conservation.

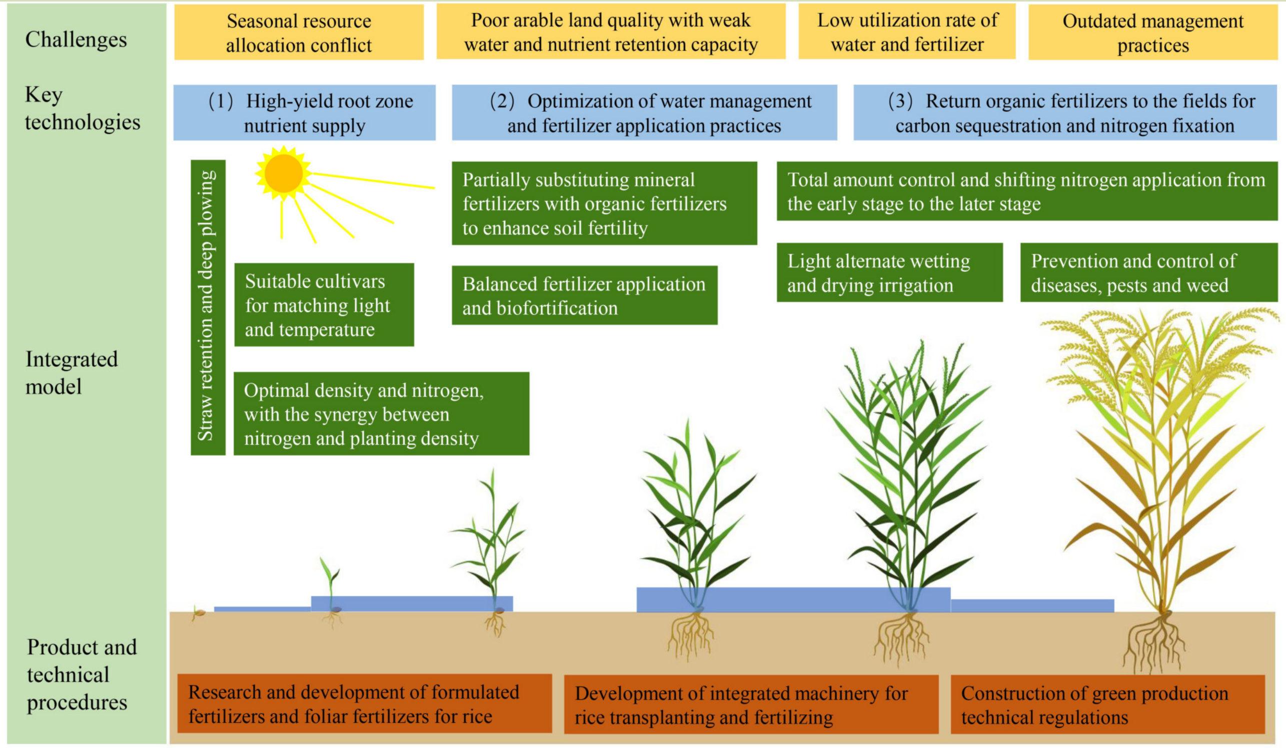


Fig. 2 Integration of regional green yield increase and efficiency improvement models.

Specific practices include straw crushing and incorporation into the field, substituting organic fertilizers for part of the mineral fertilizers, increasing soil organic matter content, improving soil structure and enhancing the ability of soil to retain water and nutrients, all of which contribute to increased crop yields[134–136]. Suitable cultivars will be selected based on the climatic conditions of each production region, with optimal sowing and transplanting times determined to maximize the use of light and temperature resources, thereby enhancing photosynthetic efficiency. Planting density will be optimized by scientifically determining plant and row spacing, and the application of N fertilizer will be precisely regulated to achieve optimal synergy. Fertilizer application strategies will be enhanced through biofortification and the development of a comprehensive nutrient management program, which incorporates multiple elements. Additionally, the use of biological fertilizers and microbial activity will help optimize nutrient release and transformation, thereby improving rice nutrient uptake efficiency. Irrigation strategies will be based on the specific water requirements at different growth stages of rice. This includes maintaining shallow water levels during early tillering to promote tiller development, reducing irrigation during late tillering when tiller formation becomes ineffective, retaining water during the booting and earing stages, and implementing alternating dry and wet conditions during the late filling stage to enhance root vitality and improve rice quality[137].

Concurrent emphasis on new product development and technical standardization is critical. We advocate for integrated water-fertilizer infrastructure to achieve irrigation-fertilizer application synergy, enabling precise resource delivery aligned with rice growth requirements. Strengthened fertilizer management systems should include stage-specific applications of base fertilizers, formulated fertilizers and foliar fertilizers to ensure continuous nutrient supply throughout the growth cycle.

6 Regional technology application model innovation

To improve the application efficacy of green, high-yield and high-efficiency technologies in diverse rice-growing regions and advance the sustainable development of the rice industry, it is essential to develop region-specific annual green, high-yield and high-efficiency technological models for rice production. These models integrate a systematic framework that bridges foundational research with practical applications (Fig. 3).

Firstly, field experiments are conducted across multiple rice production regions to analyze the nutrient requirements of rice at different growth stages. Concurrently, the soil nutrient supply mechanisms are investigated, focusing on the role of microorganisms in nutrient transformation, thereby establishing a theoretical foundation for subsequent

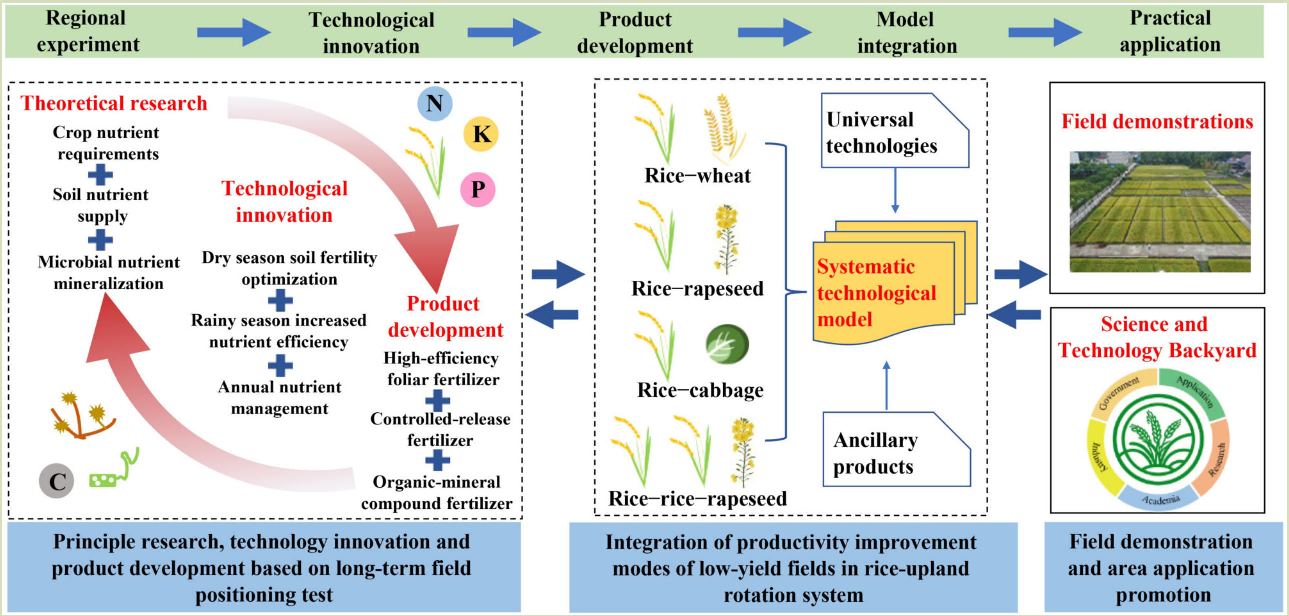


Fig. 3 Regional technology application model innovation.

technological innovations. For example, functional microorganisms are used to improve soil structure and enhance soil fertility[133]. Building upon this theoretical framework, annual green, high-yield and high-efficiency production technologies are developed to address seasonal challenges: improving soil fertility during the dry season, reducing nutrient loss in the rainy season and optimizing crop nutrient and water use efficiency.

Secondly, novel products are designed to align with technological innovations and maximize the efficacy of high-yield technologies. For example, a highly efficient foliar fertilizer is developed to rapidly replenish nutrients during critical growth phases, addressing the accelerated developmental demands of crops[138]. A specialized slow-release fertilizer for rice is formulated to synchronize nutrient release with growth requirements, minimizing fertilizer waste and improving utilization rates[139]. Also, a bio-organic-mineral compound fertilizer is created by integrating the advantages of organic and mineral fertilizers, ensuring sustained nutrient supply while meeting short-term needs.

Finally, diverse technologies and products are integrated into a comprehensive system model. Supportive products and standardized technologies are established for rotation or intercropping systems (e.g., rice–wheat, rice–rape and rice–vegetables). In rotational systems, soil improvement, precision fertilizer placement and sustainable pest control technologies are combined to address the varying growth requirements of dual crops, achieving efficient resource utilization and recycling.

To facilitate the practical application of the optimized technical model, we propose leveraging the Science and Technology Backyard platform. This initiative connects governments, enterprises, academic institutions, communities and farmers, establishing an integrated government-industry-education-research service platform to promote the adoption and dissemination of green production and efficiency technologies.

7 Conclusions

The application of green high-yield and high-efficiency technology across various experimental sites contributes to the enhancement of rice yield, reduction in fertilizer and water usage, and mitigation greenhouse gas emissions. The current state of rice production in China is affected by issues related to inadequate nutrient management and other crop production practices. Therefore, it is recommended to enhance cooperation among government, researchers and farmers by leveraging the Science and Technology Backyard platform to facilitate the large-scale adoption of green high-yield and high-efficiency technologies aimed at increasing rice yield, reducing resource consumption and achieving sustainable production.

Acknowledgements

The work was supported by National Key R&D Program of China (2023YFD1901101 and 2022YFD1901503-1) and Jiangsu Excellent Postdoctoral Program, China (2024ZB587).

Compliance with ethics guidelines

Jian Huang, Yixiao Chai, Shichao Yang, Yiwen Cao, Lei Yang, Min Wang, Xusheng Meng, and Shiwei Guo declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Bandumula N. Rice production in Asia. Key to global food security. *Proceedings of the National Academy of Sciences. India. Section B, Biological Sciences*, 2018, **88**(4): 1323–1328
2. Normile D. Reinventing rice to feed the world. *Science*, 2008, **321**(5887): 330–333
3. Cheng S H, Cao L Y, Zhuang J Y, Chen S G, Zhan X D, Fan Y Y, Zhu D F, Min S K. Super hybrid rice breeding in China: achievements and prospects. *Journal of Integrative Plant Biology*, 2007, **49**(6): 805–810
4. Peng S, Cassman K G, Virmani S S, Sheehy J, Khush G S. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. *Crop Science*, 1999, **39**(6): 1552–1559
5. Yu Y, Huang Y, Zhang W. Changes in rice yields in China since 1980 associated with cultivar improvement, climate and crop management. *Field Crops Research*, 2012, **136**: 65–75

6. Shah S F A, McKenzie B A, Gaunt R E, Marshall J W, Frampton C M. Effect of early blight (*Alternaria solani*) and different nitrogen inputs on radiation interception, radiation use efficiency, and total dry matter production in potatoes (*Solanum tuberosum*) grown in Canterbury, New Zealand. *New Zealand Journal of Crop and Horticultural Science*, 2004, **32**(3): 263–272
7. Ladha J K, Tirol-Padre A, Reddy C K, Cassman K G, Verma S, Powlson D S, van Kessel C, Richter D D, Chakraborty D, Pathak H. Global nitrogen budgets in cereals: a 50-year assessment for maize, rice, and wheat production systems. *Scientific Reports*, 2016, **6**: 19355
8. He G, Liu X, Cui Z. Achieving global food security by focusing on nitrogen efficiency potentials and local production. *Global Food Security*, 2021, **29**: 100536
9. Peng S, Huang J, Zhong X, Yang J, Wang G, Zou Y, Zhang F, Zhu Q, Buresh R, Witt C. Challenge and opportunity in improving fertilizer-nitrogen use efficiency of irrigated rice in China. *Agricultural Sciences in China*, 2002, **1**(7): 776–785
10. Food and Agricultural Organization of the United Nations Statistical Database (FAOSTAT). Food and Agriculture Data. *FAOSTAT*, 2023. Available at FAO website on June 15, 2025
11. Chen S, Elrys A S, Zhao C, Cai Z, Zhang J, Müller C. Global patterns and controls of yield and nitrogen use efficiency in rice. *Science of the Total Environment*, 2023, **898**: 165484
12. Peng S, Buresh R, Huang J, Yang J, Zou Y, Zhong X, Wang G, Zhang F. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crops Research*, 2006, **96**(1): 37–47
13. Maraseni T N, Deo R C, Qu J S, Gentle P, Neupane P R. An international comparison of rice consumption behaviours and greenhouse gas emissions from rice production. *Journal of Cleaner Production*, 2018, **172**: 2288–2300
14. Guo J H, Liu X J, Zhang Y, Shen J L, Han W X, Zhang W F, Christie P, Goulding K W T, Vitousek P M, Zhang F S. Significant acidification in major Chinese croplands. *Science*, 2010, **327**(5968): 1008–1010
15. Bremner J. Sources of nitrous oxide in soils. *Nutrient Cycling in Agroecosystems*, 1997, **49**(1/3): 7–16
16. Bueno C S, Lafarge T. Higher crop performance of rice hybrids than of elite inbreds in the tropics: 1. Hybrids accumulate more biomass during each phenological phase. *Field Crops Research*, 2009, **112**(2–3): 229–237
17. De Costa W, Weerakoon W M W, Herath H, Amaratunga K S P, Abeywardena R M I. Physiology of yield determination of rice under elevated carbon dioxide at high temperatures in a subhumid tropical climate. *Field Crops Research*, 2006, **96**(2–3): 336–347
18. Huang M, Shan S L, Zhou X F, Chen J N, Cao F B, Jiang L G, Zou Y B. Leaf photosynthetic performance related to higher radiation use efficiency and grain yield in hybrid rice. *Field Crops Research*, 2016, **193**: 87–93
19. Makino A, Osmond B. Solubilization of ribulose-1,5-bisphosphate carboxylase from the membrane-fraction of pea leaves. *Photosynthesis Research*, 1991, **29**(2): 79–85
20. Poorter H, Evans J. Photosynthetic nitrogen-use efficiency of species that differ inherently in specific leaf area. *Oecologia*, 1998, **116**(1–2): 26–37
21. Hikosaka K, Osone Y. A paradox of leaf-trait convergence: why is leaf nitrogen concentration higher in species with higher photosynthetic capacity. *Journal of Plant Research*, 2009, **122**(3): 245–251
22. Chen L S, Cheng L L. Carbon assimilation and carbohydrate metabolism of 'Concord' grape (*Vitis labrusca* L.) leaves in response to nitrogen supply. *Journal of the American Society for Horticultural Science*, 2003, **128**(5): 754–760
23. Bown H, Watt M, Mason E, Clinton P, Whitehead D. The influence of nitrogen and phosphorus supply and genotype on mesophyll conductance limitations to photosynthesis in Pinus radiata. *Tree Physiology*, 2009, **29**(9): 1143–1151
24. Ray D, Sheshshayee M S, Mukhopadhyay K, Bindumadhava H, Prasad T G, Udaya Kumar M. High nitrogen use efficiency in rice genotypes is associated with higher net photosynthetic rate at lower Rubisco content. *Biologia Plantarum*, 2003, **46**(2): 251–256
25. Hawkesford M, Griffiths S. Exploiting genetic variation in nitrogen use efficiency for cereal crop improvement. *Current Opinion in Plant Biology*, 2019, **49**: 35–42
26. Xia L, Yan X. How to feed the world while reducing nitrogen pollution. *Nature*, 2023, **613**(7942): 34–35
27. Sun Y M, Gao L M, Meng X S, Huang J, Guo J J, Zhou X, Fu G H, Xu Y, Firbank L G, Wang M, Ling N, Feng X, Shen Q, Guo S. Large-scale exploration of nitrogen utilization efficiency in Asia region for rice crop: variation patterns and determinants. *Global Change Biology*, 2023, **29**(18): 5367–5378
28. Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, Zhang W, Mi G, Miao Y, Li X, Gao Q, Yang J, Wang Z, Ye Y, Guo S, Lu J, Huang J, Lv S, Sun Y, Liu Y, Peng X, Ren J, Li S, Deng X, Shi X, Zhang Q, Yang Z, Tang L, Wei C, Jia L, Zhang J, He M, Tong Y, Tang Q, Zhong X, Liu Z, Cao N, Kou C, Ying H, Yin Y, Jiao X, Zhang Q, Fan M, Jiang R, Zhang F, Dou Z. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 2018, **555**(7696): 363–366
29. Zhang W, Cao G, Li X, Zhang H, Wang C, Liu Q, Chen X, Cui Z, Shen J, Jiang R, Mi G, Miao Y, Zhang F, Dou Z. Closing yield gaps in China by empowering smallholder farmers. *Nature*, 2016, **537**(7622): 671–674
30. Jiao X, Zhang H, Ma W, Wang C, Li X, Zhang F. Science and Technology Backyard: a novel approach to empower smallholder farmers for sustainable intensification of agriculture in China. *Journal of Integrative Agriculture*, 2019, **18**(8): 1657–1666
31. Zhao Y, Wang M, Hu S, Zhang X, Ouyang Z, Zhang G, Huang B, Zhao S, Wu J, Xie D, Zhu B, Yu D, Pan X, Xu S, Shi X. Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. *Proceedings of the National Academy of Sciences of the United States of America*, 2018, **115**(16):

4045–4050

32. Liu Y, Yang J, He W, Ma J, Gao Q, Lei Q, He P, Wu H, Ullah S, Yang F. Provincial potassium balance of farmland in China between 1980 and 2010. *Nutrient Cycling in Agroecosystems*, 2017, **107**(2): 247–264
33. He P, Yang L, Xu X, Zhao S, Chen F, Li S, Tu S, Jin J, Johnston A. Temporal and spatial variation of soil available potassium in China (1990–2012). *Field Crops Research*, 2015, **173**: 49–56
34. Ling Y, Hu Q, Fu D, Zhang K, Xing Z, Gao H, Wei H, Zhang H. Optimum seeding density and seedling age for the outstanding yield performance of *Japonica* rice using crop straw boards for seedling cultivation. *Frontiers in Plant Science*, 2024, **15**: 1431687
35. Li Y, Liu Y, Wang Y, Ding Y, Wang S, Liu Z, Li G. Effects of seedling age on the growth stage and yield formation of hydroponically grown long-mat rice seedlings. *Journal of Integrative Agriculture*, 2020, **19**(7): 1755–1767
36. Singh T, Upadhyay K C. Effect of planting density and number of seedlings per hill on certain yield and quality traits in rice. *Indian Journal of Agricultural Research*, 2015, **49**(3): 270–273
37. Liu Q, Zhou X, Li J, Xin C. Effects of seedling age and cultivation density on agronomic characteristics and grain yield of mechanically transplanted rice. *Scientific Reports*, 2017, **7**(1): 14072
38. Xu G, Lu D, Wang H, Li Y. Morphological and physiological traits of rice roots and their relationships to yield and nitrogen utilization as influenced by irrigation regime and nitrogen rate. *Agricultural Water Management*, 2018, **203**: 385–394
39. Xu Z, Ye L, Shen Q, Zhang G. Advances in the study of waterlogging tolerance in plants. *Journal of Integrative Agriculture*, 2024, **23**(9): 2877–2897
40. Li H. Rice varietal improvement and rice production in China. *Journal of University of Chinese Academy of Sciences*, 2007, **24**(1): 1–8 (in Chinese)
41. Ye J, Zhang M, Yuan X, Hu D, Zhang Y, Xu S, Li Z, Li R, Liu J, Sun Y, Wang S, Feng Y, Xu Q, Yang Y, Wei X. Genomic insight into genetic changes and shaping of major inbred rice cultivars in China. *New Phytologist*, 2022, **236**(6): 2311–2326
42. Huang M. The decreasing area of hybrid rice production in China: causes and potential effects on Chinese rice self-sufficiency. *Food Security*, 2022, **14**(1): 267–272
43. Zeng B, Sun S, Wang J. Registration of main rice varieties and its application in recent 30 years in China. *Crops*, 2018, (2): 1–5 (in Chinese)
44. Nakano H, Morita S, Kitagawa H, Wada H, Takahashi M. Grain yield response to planting density in forage rice with a large number of spikelets. *Crop Science*, 2012, **52**(1): 345–350
45. Huang M, Yang C, Ji Q, Jiang L, Tan J, Li Y. Tillering responses of rice to plant density and nitrogen rate in a subtropical environment of southern China. *Field Crops Research*, 2013, **149**: 187–192
46. Li G, Zhang J, Yang C, Liu Z, Wang S, Ding Y. Population characteristics of high-yielding rice under different densities. *Agronomy Journal*, 2016, **108**(4): 1415–1423
47. Clerget B, Bueno C, Domingo A, Layaoen H, Vial L. Leaf emergence, tillering, plant growth, and yield in response to plant density in a high-yielding aerobic rice crop. *Field Crops Research*, 2016, **199**: 52–64
48. Zhao L, Zhou H, Tang L, Na Y, Duan S, Zheng D, Feng N, Shen X. Optimizing nitrogen dosage and planting density to improve *Japonica* rice yield. *Agronomy*, 2024, **14**(8): 1738
49. Huang M, Zou Y. Integrating mechanization with agronomy and breeding to ensure food security in China. *Field Crops Research*, 2018, **224**: 22–27
50. Zhu X, Zhang J, Zhang Z, Deng A, Zhang W. Dense planting with less basal nitrogen fertilization might benefit rice cropping for high yield with less environmental impacts. *European Journal of Agronomy*, 2016, **75**: 50–59
51. Wei Z, Zhang Y, Liu Z, Peng M, Wang T, Cao N. Change in phosphorus requirement with increasing grain yield for rice under saline-sodic stress in Northeast China. *Frontiers in Environmental Science*, 2022, **10**: 953579
52. Wang S, Yang M, Liao S, Sheng W, Shi X, Lu J, Guo S, Shen J, Zhang F, Goulding K, Liu X. Yield and the 15N fate in rice/maize season in the Yangtze River Basin. *Agronomy Journal*, 2019, **111**(2): 517–527
53. Liu R, Wang Y, Hong Y, Wang F, Mao X, Yi J. Controlled-release urea application and optimized nitrogen applied strategy reduced nitrogen leaching and maintained grain yield of paddy fields in Northwest China. *Frontiers in Plant Science*, 2023, **14**: 1033506
54. Zhang A, Gao J, Liu R, Zhang Q, Chen Z, Yang S, Yang Z. Using side-dressing technique to reduce nitrogen leaching and improve nitrogen recovery efficiency under an irrigated rice system in the upper reaches of Yellow River Basin, Northwest China. *Journal of Integrative Agriculture*, 2016, **15**(1): 220–231
55. Lv Z, Zhu Y, Liu X, Ye H, Tian Y, Li F. Climate change impacts on regional rice production in China. *Climatic Change*, 2018, **147**(3-4): 523–537
56. Guo E, Wang L, Jiang S, Xiang H, Shi Y, Chen X, Cheng X, Wang X, Zhang T, Wang L, Feng Y, Lai Y, Li T, Yang X. Impacts of chilling at the tillering phases on rice growth and grain yield in Northeast China. *Journal Agronomy & Crop Science*, 2022, **208**(4): 510–522
57. Shi Y, Wang L, Jiang S, Guo E, Li T, Zhou L, Zhang W, Ma H, Guan K, Li E, Zhang T, Yang X. An experimental study on the effects of intermittent chilling at different growth stages on rice yield in Northeast China. *Journal Agronomy & Crop Science*, 2023, **209**(3): 317–329
58. Qiao L, Wang X, Smith P, Fan J, Lu Y, Emmett B, Li R, Dorling S, Chen H, Liu S, Benton T G, Wang Y, Ma Y, Jiang R, Zhang F, Piao S, Müller C, Yang H, Hao Y, Li W, Fan M. Soil quality both increases crop production and improves resilience to climate change. *Nature Climate Change*, 2022, **12**(6): 574–580

59. Gu Z, Xie Y, Gao Y, Ren X, Cheng C, Wang S. Quantitative assessment of soil productivity and predicted impacts of water erosion in the black soil region of northeastern China. *Science of the Total Environment*, 2018, **637–638**: 706–716
60. Xu X, Xu Y, Chen S, Xu S, Zhang H. Soil loss and conservation in the black soil region of Northeast China: a retrospective study. *Environmental Science & Policy*, 2010, **13**(8): 793–800
61. Wang W, Deng X, Yue H. Black soil conservation will boost China's grain supply and reduce agricultural greenhouse gas emissions in the future. *Environmental Impact Assessment Review*, 2024, **106**: 107482
62. Cong R, Zhang Z, Lu J, Li X, Ren T, Wang W. Evaluation of nitrogen requirement and efficiency of rice in the region of Yangtze River Valley based on large-scale field experiments. *Journal of Integrative Agriculture*, 2015, **14**(10): 2090–2098
63. Wang X, Zhu B, Hua K, Luo Y, Zhang J, Zhang A. Assessment of soil organic carbon stock in the upper Yangtze River basin. *Journal of Mountain Science*, 2013, **10**(5): 866–872
64. Zhang Y, Wu H, Yao M, Zhou J, Wu K, Hu M, Shen H, Chen D. Estimation of nitrogen runoff loss from croplands in the Yangtze River Basin: a meta-analysis. *Environmental Pollution*, 2021, **272**: 116001
65. Liu X, Wang H, Zhou J, Hu F, Zhu D, Chen Z, Liu Y. Effect of N fertilization pattern on rice yield, N use efficiency and fertilizer-N fate in the Yangtze River Basin, China. *PLoS One*, 2016, **11**(11): e0166002
66. Chen C, van Groenigen K J, Yang H, Hungate B A, Yang B, Tian Y, Chen J, Dong W, Huang S, Deng A, Jiang Y, Zhang W. Global warming and shifts in cropping systems together reduce China's rice production. *Global Food Security*, 2020, **24**: 100359
67. Giorno F, Wolters-Arts M, Mariani C, Rieu I. Ensuring reproduction at high temperatures: the heat stress response during anther and pollen development. *Plants*, 2013, **2**(3): 489–506
68. Zhang W, Yu Y, Huang Y, Li T, Wang P. Modeling methane emissions from irrigated rice cultivation in China from 1960 to 2050. *Global Change Biology*, 2011, **17**(12): 3511–3523
69. Huang T, Wang Z, Guo L, Li H, Tan M, Zou J, Zong R, Dhital Y. The impact of long-term mulched drip irrigation on soil particle composition and salinity in arid Northwest China. *Agronomy*, 2024, **14**(3): 599
70. Peng S, Buresh R, Huang J, Zhong X, Zou Y, Yang J, Wang G, Liu Y, Hu R, Tang Q, Cui K, Zhang F, Dobermann A. Improving nitrogen fertilization in rice by site-specific N management. A review. *Agronomy for Sustainable Development*, 2010, **30**(3): 649–656
71. Ottis B, Talbert R. Rice yield components as affected by cultivar and seeding rate. *Agronomy Journal*, 2005, **97**(6): 1622–1625
72. Fageria N, Slaton N, Baligar V. Nutrient management for improving lowland rice productivity and sustainability. *Advances in Agronomy*, 2003, **80**: 63–152
73. Zhong X, Peng S, Sheehy J, Visperas R, Liu H. Relationship between tillering and leaf area index: quantifying critical leaf area index for tillering in rice. *Journal of Agricultural Science*, 2002, **138**(3): 269–279
74. Xu C, Wang D, Shao G, Zhang X. Effects of transplanting density and nitrogen fertilizer rate on yield formation and grain quality of super high yielding rice Zhongzao 22. *Chinese Journal of Rice Science*, 2008, **22**(5): 507–512 (in Chinese)
75. Sui B, Feng X, Tian G, Hu X, Shen Q, Guo S. Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. *Field Crops Research*, 2013, **150**: 99–107
76. Kamiji Y, Yoshida H, Palta J, Sakuratani T, Shiraiwa T. N applications that increase plant N during panicle development are highly effective in increasing spikelet number in rice. *Field Crops Research*, 2011, **122**(3): 242–247
77. Makino A, Shimada T, Takumi S, Kaneko K, Matsuoka M, Shimamoto K, Nakano H, Miyao-Tokutomi M, Mae T, Yamamoto N. Does decrease in ribulose-1,5-bisphosphate carboxylase by antisense RbcS lead to a higher N-use efficiency of photosynthesis under conditions of saturating CO_2 and light in rice plants. *Plant Physiology*, 1997, **114**(2): 483–491
78. Fukayama H, Ueguchi C, Nishikawa K, Katoh N, Ishikawa C, Masumoto C, Hatanaka T, Misoo S. Overexpression of rubisco activase decreases the photosynthetic CO_2 assimilation rate by reducing rubisco content in rice leaves. *Plant & Cell Physiology*, 2012, **53**(6): 976–986
79. Li Y, Gao Y, Xu X, Shen Q, Guo S. Light-saturated photosynthetic rate in high-nitrogen rice (*Oryza sativa* L.) leaves is related to chloroplastic CO_2 concentration. *Journal of Experimental Botany*, 2009, **60**(8): 2351–2360
80. Meng X, Pan Y, Chai Y, Ji Y, Du H, Huang J, Chen S, Wang M, Guo S. Higher light utilization and assimilate translocation efficiency produced greater grain yield in super hybrid rice. *Plant and Soil*, 2024, **504**(1–2): 529–544
81. Tian G, Gao L, Kong Y, Hu X, Xie K, Zhang R, Ling N, Shen Q, Guo S. Improving rice population productivity by reducing nitrogen rate and increasing plant density. *PLoS One*, 2017, **12**(8): e0182310
82. Hou W, Tränkner M, Lu J, Yan J, Huang S, Ren T, Cong R, Li X. Interactive effects of nitrogen and potassium on photosynthesis and photosynthetic nitrogen allocation of rice leaves. *BMC Plant Biology*, 2019, **19**(1): 302
83. Zhang C, Feng B, Chen T, Fu W, Li H, Li G, Jin Q, Tao L, Fu G. Heat stress-reduced kernel weight in rice at anthesis is associated with impaired source-sink relationship and sugars allocation. *Environmental and Experimental Botany*, 2018, **155**: 718–733
84. Lv X, Zhang Y, Zhang Y, Fan S, Kong L. Source-sink modifications affect leaf senescence and grain mass in wheat as revealed by proteomic analysis. *BMC Plant Biology*, 2020, **20**(1): 257
85. Dai X, Song D, Zhou W, Liu G, Liang G, He P, Sun G, Yuan F,

Liu Z, Yao Y, Cui J. Partial substitution of chemical nitrogen with organic nitrogen improves rice yield, soil biochemical indictors and microbial composition in a double rice cropping system in South China. *Soil & Tillage Research*, 2021, **205**: 104753

86. Pan Y, Guo J, Fan L, Ji Y, Liu Z, Wang F, Pu Z, Ling N, Shen Q, Guo S. The source-sink balance during the grain filling period facilitates rice production under organic fertilizer substitution. *European Journal of Agronomy*, 2022, **134**: 126468
87. Watson C A, Atkinson D, Gosling P, Jackson L R, Rayns F W. Managing soil fertility in organic farming systems. *Soil Use and Management*, 2002, **18**(s1): 239–247
88. Kong X, Zhang F, Wei Q, Xu Y, Hui J. Influence of land use change on soil nutrients in an intensive agricultural region of North China. *Soil & Tillage Research*, 2006, **88**(1–2): 85–94
89. Vitousek P, Naylor R, Crews T, David M, Drinkwater L, Holland E, Johnes P, Katzenberger J, Martinelli L, Matson P, Nziguheba G, Ojima D, Palm C A, Robertson G P, Sanchez P A, Townsend A R, Zhang F S. Nutrient imbalances in agricultural development. *Science*, 2009, **324**(5934): 1519–1520
90. Stamatiadis S, Werner M, Buchanan M. Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). *Applied Soil Ecology*, 1999, **12**(3): 217–225
91. Shang Q, Ling N, Feng X, Yang X, Wu P, Zou J, Shen Q, Guo S. Soil fertility and its significance to crop productivity and sustainability in typical agroecosystem: a summary of long-term fertilizer experiments in China. *Plant and Soil*, 2014, **381**(1–2): 13–23
92. Wu Y, Tian X, Tong Y, Nan X, Zhou M, Hou Y. Assessment of integrated soil fertility index based on principal components analysis. *Chinese Journal of Ecology*, 2010, **29**(1): 173–180 (in Chinese)
93. Reeves D. The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil & Tillage Research*, 1997, **43**(1–2): 131–167
94. Manna M, Swarup A, Wanjari R, Ravankar H, Mishra B, Saha M, Singh Y, Sahi D, Sarap P. Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research*, 2005, **93**(2–3): 264–280
95. Loeppmann S, Blagodatskaya E, Pausch J, Kuzyakov Y. Substrate quality affects kinetics and catalytic efficiency of exo-enzymes in rhizosphere and detritusphere. *Soil Biology & Biochemistry*, 2016, **92**: 111–118
96. Zak D, Blackwood C, Waldrop M. A molecular dawn for biogeochemistry. *Trends in Ecology & Evolution*, 2006, **21**(6): 288–295
97. Zechmeister-Boltenstern S, Keiblinger K, Mooshammer M, Peñuelas J, Richter A, Sardans J, Wanek W. The application of ecological stoichiometry to plant-microbial-soil organic matter transformations. *Ecological Monographs*, 2015, **85**(2): 133–155
98. Li F, Chen L, Zhang J, Yin J, Huang S. Bacterial community structure after long-term organic and inorganic fertilization reveals important associations between soil nutrients and specific taxa involved in nutrient transformations. *Frontiers in Microbiology*, 2017, **8**: 187
99. Guo J, Liu W, Zhu C, Luo G, Kong Y, Ling N, Wang M, Dai J, Shen Q, Guo S. Bacterial rather than fungal community composition is associated with microbial activities and nutrient-use efficiencies in a paddy soil with short-term organic amendments. *Plant and Soil*, 2018, **424**(1–2): 335–349
100. Wang G, Cui Z, Chen X, Zhang F, Zhang J, Wang S. Reactive nitrogen loss pathways and their effective factors in paddy field in southern China. *Chinese Journal of Applied Ecology*, 2015, **26**(8): 2337–2345 (in Chinese)
101. Wu Y, Gu B, Erisman J, Reis S, Fang Y, Lu X, Zhang X. $PM_{2.5}$ pollution is substantially affected by ammonia emissions in China. *Environmental Pollution*, 2016, **218**: 86–94
102. Landman W. Climate change 2007: the physical science basis. *South African Geographical Journal*, 2010, **92**(1): 86–87
103. Pang B, Zhang J, Wu J, Li Z, Jiang J. Effects of the veterinary antibiotic sulfamethazine on ammonia volatilization from a paddy field treated with conventional synthetic fertilizer and manure. *Environmental Sciences*, 2018, **39**(7): 3460–3466 (in Chinese)
104. Hu M, Wade A, Shen W, Zhong Z, Qiu C, Lin X. Effects of organic fertilizers produced using different techniques on rice grain yield and ammonia volatilization in double-cropping rice fields. *Pedosphere*, 2024, **34**(1): 110–120
105. Shang Q, Gao C, Yang X, Wu P, Ling N, Shen Q, Guo S. Ammonia volatilization in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. *Biology and Fertility of Soils*, 2014, **50**(5): 715–725
106. Jongkaewwattana S, Geng S. Effect of nitrogen and water management on panicle development and milling quality of California rice (*Oryza-Sativa* L). *Journal Agronomy & Crop Science*, 1991, **167**(1): 43–52
107. Zhou W, Yan F, Chen Y, Ren W. Optimized nitrogen application increases rice yield by improving the quality of tillers. *Plant Production Science*, 2022, **25**(3): 311–319
108. Ciampitti I, Vyn T. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. *Field Crops Research*, 2011, **121**(1): 2–18
109. de Campos M, Rossato O B, Marasca I, Martello J M, de Siqueira G F, Garcia C P, Rossetto R, Calonego J C, Cantarella H, Crusciol C A C. Deep tilling and localized liming improve soil chemical fertility and sugarcane yield in clayey soils. *Soil & Tillage Research*, 2022, **222**: 105425
110. Li X, Wei B, Xu X, Zhou J. Effect of deep vertical rotary tillage on soil properties and sugarcane biomass in rainfed dry-land regions of Southern China. *Sustainability*, 2020, **12**(23): 10199

111. Scarpare F V, van Lier Q D, de Camargo L, Pires R C M, Ruiz-Corrêa S T, Bezerra A H F, Gava G J C, Dias C T S. Tillage effects on soil physical condition and root growth associated with sugarcane water availability. *Soil & Tillage Research*, 2019, **187**: 110–118
112. Chen X, Luo X, Wang Z, Zhang M, Hu L, Zeng S, Mo Z. Experiment of synchronous side deep fertilizing technique with rice hill-drop drilling. *Transactions of the Chinese Society of Agricultural Engineering*, 2014, **30**(16): 1–7 (in Chinese)
113. Zhou X, Huang T, Peng J, Lu W, Kang X, Sun M, Song S, Tang Q, Chen Y, Zhan D, Zhou X. Effects of machine-transplanting synchronized with one-time precision fertilization on nutrient uptake and use efficiency of double cropping rice. *Chinese Journal of Rice Science*, 2019, **33**(5): 436–446 (in Chinese)
114. Wang D, Ye C, Xu C, Wang Z, Chen S, Chu G, Zhang X. Soil nitrogen distribution and plant nitrogen utilization in direct-seeded rice in response to deep placement of basal fertilizer-nitrogen. *Rice Science*, 2019, **26**(6): 404–415
115. Zhong X, Peng J, Kang X, Wu Y, Luo G, Hu W, Zhou X. Optimizing agronomic traits and increasing economic returns of machine-transplanted rice with side-deep fertilization of double-cropping rice system in southern China. *Field Crops Research*, 2021, **270**: 108191
116. Zhong X, Zhou X, Luo G, Huang Y, Wu Y, Cao R, Tian C, Peng J. Soil mineral nitrogen, soil urease activity, nitrogen losses and nitrogen footprint under machine-planted rice with side-deep fertilization. *Plant and Soil*, 2024, **494**(1–2): 185–202
117. Maclean J L, Dawe D C, Hardy B, Hettel G P. Rice Almanac, 3rd ed. Wallingford, Oxon: *CABI Publishing*, 2002
118. National Bureau of Statistics of China (NBSC). China Statistical Yearbook. Beijing: *China Statistics Press*, 2022 (in Chinses)
119. Feng Z Y, Qin T, Du X Z, Sheng F, Li C F. Effects of irrigation regime and rice variety on greenhouse gas emissions and grain yields from paddy fields in central China. *Agricultural Water Management*, 2021, **250**: 106830
120. Liang K, Zhong X, Huang N, Lampayan R, Liu Y, Pan J, Peng B, Hu X, Fu Y. Nitrogen losses and greenhouse gas emissions under different N and water management in a subtropical double-season rice cropping system. *Science of the Total Environment*, 2017, **609**: 46–57
121. Lampayan R, Rejesus R, Singleton G, Bouman B. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, 2015, **170**: 95–108
122. Runkle B R K, Suvočarev K, Reba M L, Reavis C W, Smith S F, Chiu Y L, Fong B. Methane emission reductions from the alternate wetting and drying of rice fields detected using the eddy covariance method. *Environmental Science & Technology*, 2019, **53**(2): 671–681
123. Liang K, Zhong X, Huang N, Lampayan R, Pan J, Tian K, Liu Y. Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in South China. *Agricultural Water Management*, 2016, **163**: 319–331
124. Zhang Y, Peng X, Luo S, Liu Y, Song W, Su D. Effects of zinc application on returning green and yield of rice in cold area. *Chinese Journal of Soil Science*, 2013, **44**(2): 437–441 (in Chinese)
125. Fei L, Pan Y, Ma H, Guo R, Wang M, Ling N, Shen Q, Guo S. Optimal organic-inorganic fertilization increases rice yield through source-sink balance during grain filling. *Field Crops Research*, 2024, **308**: 109285
126. Zhao C, Huang H, Qian Z, Jiang H, Liu G, Xu K, Hu Y, Dai Q, Huo Z. Effect of side deep placement of nitrogen on yield and nitrogen use efficiency of single season late japonica rice. *Journal of Integrative Agriculture*, 2021, **20**(6): 1487–1502
127. Peng X, Yang Y, Yu C, Chen L, Zhang M, Liu Z, Sun Y, Luo S, Liu Y. Crop management for increasing rice yield and nitrogen use efficiency in Northeast China. *Agronomy Journal*, 2015, **107**(5): 1682–1690
128. Zhong X, Liang K, Pan J, Fu Y, Hu X, Huang N, Liu Y, Hu R, Li M, Wang X, Ye Q, Yin Y. Research progress on low-carbon and high-yield cultivation technology for double-cropping rice in South China. *Journal of South China Agricultural University*, 2023, **44**(6): 867–874 (in Chinese)
129. Buhailiqem A, Zhu C, Yuan J, Zhang Y, Zhao Z, Wen X, Wang S, Kang M, Tang F, Wang F, Zhang J. Effects of irrigation and nitrogen fertilizer application on growth, yield and quality of different rice varieties in arid areas of Xinjiang. *Plant Genetic Resources*, 2022, **20**(5): 309–318
130. Guo S, Yu H, Zeng X, Shangguan Y, Zhou Z, Li X, Liu Z, He M, Luo X, Ouyang Y, Liu S, Wei L, Qin Y, Chen K. Balancing yield and environmental impact: nitrogen management and planting density for rice in Southwest China. *Agronomy*, 2024, **14**(8): 1843
131. Ding Y, Wang W, Song R, Shao Q, Jiao X, Xing W. Modeling spatial and temporal variability of the impact of climate change on rice irrigation water requirements in the middle and lower reaches of the Yangtze River, China. *Agricultural Water Management*, 2017, **193**: 89–101
132. Jin Q, Wang C, Sardans J, Vancov T, Fang Y, Wu L, Huang X, Gargallo-Garriga A, Peñuelas J, Wang W. Effect of soil degradation on the carbon concentration and retention of nitrogen and phosphorus across Chinese rice paddy fields. *Catena*, 2022, **209**: 105810
133. Li S, Zhuang Y, Liu H, Wang Z, Zhang F, Lv M, Zhai L, Fan X, Niu S, Chen J, Xu C, Wang N, Ruan S, Shen W, Mi M, Wu S, Du Y, Zhang L. Enhancing rice production sustainability and resilience via reactivating small water bodies for irrigation and drainage. *Nature Communications*, 2023, **14**(1): 3794
134. Liu L, Liu D, Ding X, Chen M, Zhang S. Straw incorporation and nitrogen fertilization enhance soil carbon sequestration by altering soil aggregate and microbial community composition in saline-alkali soil. *Plant and Soil*, 2024, **498**(1–2): 341–356
135. Xia H, Shen J, Riaz M, Jiang C, Zu C, Jiang C, Liu B. Effects of

biochar and straw amendment on soil fertility and microbial communities in paddy soils. *Plants*, 2024, **13**(11): 1478

136. Song K, Yang J, Xue Y, Lv W, Zheng X, Pan J. Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. *Scientific Reports*, 2016, **6**(1): 36602
137. Qi D, Zhu J, Wang X. Root growth in rice (Liangyou 152) under alternate wetting and drying irrigation and mixed application of polymer-coated and common urea. *Journal of Soil Science and Plant Nutrition*, 2023, **23**(4): 6838–6850
138. Ishfaq M, Kiran A, Rehman H, Farooq M, Ijaz N, Nadeem F, Azeem I, Li X, Wakeel A. Foliar nutrition: potential and challenges under multifaceted agriculture. *Environmental and Experimental Botany*, 2022, **200**: 104909
139. Shanmugavel D, Rusyn I, Solorza-Feria O, Kamaraj S. Sustainable SMART fertilizers in agriculture systems: a review on fundamentals to in-field applications. *Science of the Total Environment*, 2023, **904**: 166729