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Field Evaluation of Nitrogen-use Efficient Rice Varieties under Varying Fertilizer Regimes

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Abstract Improving the nitrogen use efficiency (NUE) of rice is of great significance for ensuring crop yield while reducing the environmental impact caused by excessive nitrogen application. This study focuses on the field performance assessment of high-nitrogen-efficient rice varieties under different fertilization patterns, covering strategies such as conventional fertilization, reduced fertilization, slow-release fertilization, and organic combined fertilization. It analyzes the performance of the varieties in terms of nitrogen absorption, utilization efficiency, and yield composition, and screens the varieties suitable for the development of green agriculture - the optimal fertilization combination Through field trials conducted in major rice-growing areas in China (such as the middle and lower reaches of the Yangtze River, the main production areas in Northeast China, and the double-cropping rice-growing areas in South China), the responses and adaptability of different varieties to fertilization patterns were compared. Research has found that different rice varieties with high nitrogen efficiency show significant differences under different nitrogen application conditions, indicating that species-specific fertilization optimization is of great significance for improving nitrogen recovery rate and yield. This study provides a theoretical basis and practical path for constructing an efficient and low-input rice cultivation system, and offers scientific support for subsequent research on the genotype-fertilization interaction mechanism and the formulation of green agricultural policies.
Keywords Rice; Fertilization mode; Nitrogen use efficiency (NUE); Field experiment; Green agriculture

1 Introduction

For many people, a bowl of rice is nothing, but on a global scale, rice is a staple food that more than half of the population cannot do without every day. It is precisely for this reason that in order to maintain a stable job in the future, production must be increased. Among them, nitrogen (N) is an unavoidable keyword - it is the main "booster" for the growth and development of rice, and has a direct impact on both yield and quality. For decades, by continuously increasing nitrogen application, the total output of rice has indeed been pushed up. However, problems have also emerged: only about 40% to 50% of the fertilizer applied can be absorbed and utilized by rice, while the rest either seeps into water, drifts into the air, or becomes greenhouse gases, ultimately affecting farmers' income. While ensuring stable production and supply, it is also necessary to safeguard the environmental bottom line. At this point, "improving nitrogen fertilizer utilization rate" has truly become a hard indicator in the global rice-growing system.

In recent years, researchers have not been idle either. It seems a feasible approach to make changes in breeding by increasing the nitrogen fertilizer utilization rate (NUE) to relieve the pressure. Relevant genes, such as those responsible for nitrogen absorption, transport and assimilation, are being identified one by one and attempts are being made to introduce them into existing superior varieties (Hu et al., 2022; Wang et al., 2022; Xin et al., 2025). With the increasing maturity of tools such as molecular breeding and GWAS, the breeding efficiency is also accelerating, which is expected to bring those new varieties that are "fertilizer-saving and high-yielding" to the fields earlier. But relying solely on the variety is not enough; it also depends on whether the fertilization plan can keep up. Only with the "dual-wheel drive" of variety and management can the biological potential be truly transformed into stable production and environmental protection.

This study aims to evaluate the field performance of rice varieties that efficiently utilize nitrogen fertilizers under different fertilization schemes. It integrates agronomic experiments, genetic analysis, and nitrogen fertilizer utilization rate (NUE) assessment to screen out varieties that can maintain yield and quality at lower nitrogen input, and quantify the yield and nitrogen fertilizer utilization rate responses of different rice genotypes under different fertilization gradients. Clarify the genotype-environmental interactions that affect nitrogen fertilizer utilization rate. This study aims to promote sustainable rice production by guiding breeding programs and fertilizer recommendations, and ultimately contribute to global food security and environmental protection.

2 Physiological Basis of Nitrogen-efficient Rice Varieties

2.1 Molecular mechanisms of nitrogen uptake, transport, and assimilation

For rice to make efficient use of nitrogen fertilizer, it does not rely on a single link but on a complete set of internal operation procedures. Absorbing nitrogen from the soil is just the first step. Next, a series of molecular mechanisms are needed to truly "utilize" this nitrogen. Like OsNRT1.1B, OsNPF6.1 and OsAMT1; These transport proteins are used to transport nitrates and ammonium. Enzymes such as NR, NiR, GS, and GOGAT are responsible for converting nitrogen into amino acids and proteins needed by crops (Shen, 2025). Interestingly, these molecules themselves are also controlled by regulatory factors, such as OsNAC42, and gene loci like DNR1 and DEP1, which determine whether rice can "intelligently" absorb and utilize nitrogen in different environments (Figure 1) (Tang et al., 2019). Not all rice varieties have this ability. Some varieties are just good at regulating and thus have a higher utilization rate.

2.2 Genetic basis of nitrogen use efficiency variation among varieties

Why can some rice varieties achieve "low fertilizer consumption and high yield" while others cannot? This is inseparable from genetic differences. In the past, through analyses such as QTL and GWAS, researchers have identified a number of key loci related to nitrogen efficiency, such as qTGW11, OsNR2, OsNRT1.1B and OsTCP19, which all affect nitrogen uptake, nitrogen utilization and final yield performance of rice (Liu et al., 2022; Shen et al., 2025). Especially between indica rice and japonica rice, some natural allelic differences can affect the pathways of nitrate assimilation or hormone regulation, thereby directly causing differences in expression (Gao et al., 2019). The good genes "dug" out from wild rice or local old varieties were later introduced into modern varieties, and indeed some varieties performed more stably in low-nitrogen environments. So, when it comes to breeding, the selection of genetic materials is really crucial.

2.3 Evaluation indices and phenotypic traits related to nitrogen efficiency

Ultimately, to determine whether a rice variety has a good nitrogen efficiency or not, one needs to observe how it performs in the field. Efficiency indicators like NUpE and NUtE may sound academic, but in fact, they are about how much nitrogen is absorbed, how much nitrogen is used, and how much grain is finally produced (Shanmugapriya et al., 2025). For some varieties, even with low fertilizer application, the root structure can hold up, and the photosynthetic capacity of flag leaves is not compromised. Parameters such as F_v/F_m and ΦPSII also perform well (Natarajan et al., 2024). Nowadays, there are still some high-throughput tools, such as unmanned aerial vehicles with multispectral cameras flying around, which can directly monitor the changes in canopy nitrogen content. These phenotypic characteristics and technical means are increasingly being used to select superior genotypes suitable for low-nitrogen cultivation, which not only saves fertilizer but also ensures yield, providing significant assistance for sustainable rice production (Zhu, 2025).

3 Fertilization Regimes and Their Agricultural Implications

3.1 Comparison of conventional, reduced, and slow-release fertilizer strategies

For a long time, the conventional practice in rice fields has been to apply quick-acting urea multiple times. To put it bluntly, it's for convenience and quick results. However, the result of doing so is that the utilization rate of nitrogen fertilizer is not high and it is also prone to loss. A considerable amount of nitrogen was carried away with water and entered the atmosphere and water bodies, and environmental pressure followed (Lee et al., 2025). So, reducing the amount of fertilizer application seems like a solution, especially on the basis of adjusting the timing of fertilizer application. However, this approach is not a panacea. If not used properly, the yield may even drop.

Some people began to try slow-release and controlled-release fertilizers (SCRF) - such as those coated fertilizers or granular mixed types - the advantage is that the fertilization rhythm is more in line with the needs of rice, the dosage is more precise, and the effect is much more stable. Many experiments and data summaries show that such practices can increase the yield by 6% to 24%, and the efficiency of nitrogen fertilizer utilization also improves accordingly, with a maximum increase of 53% (Jiang et al., 2023). Of course, to be fair, although these new types of fertilizers are good, their costs and technical thresholds are indeed not low, and they are not so easy to promote.

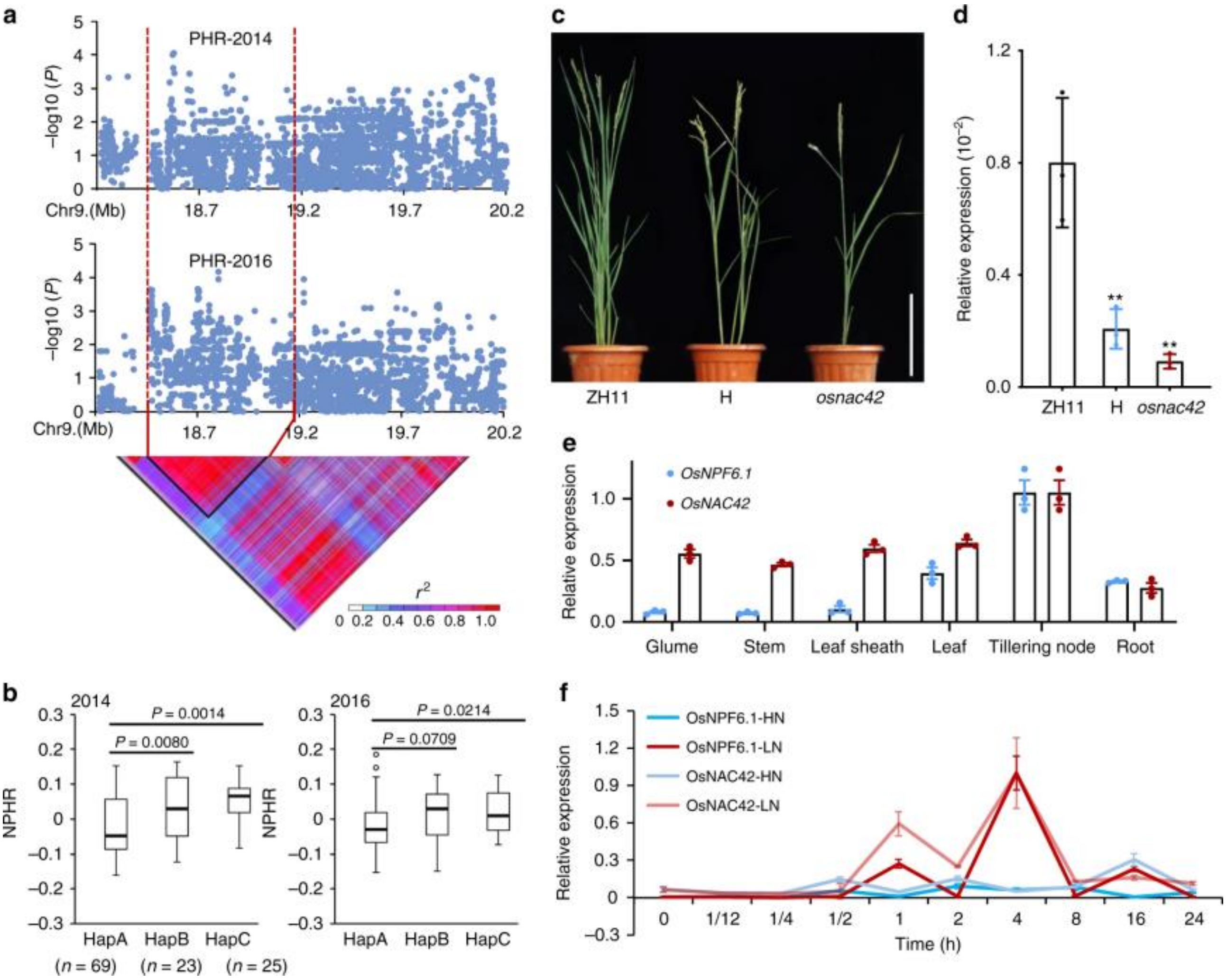

Figure 1 Identification and functional validation of the transcription factor OsNAC42 on chromosome 9. a Local Manhattan plot (top) and LD heatmap (bottom) surrounding the peak on chromosome 9. Red dashed lines indicate the candidate region for the peak. b Comparative analyses of OsNAC42 between the low and high NUE haplotypes. Boxplots for NPHR (normalized plant height ratio)-2014 (top) and NPHR-2016 (bottom) based on the haplotypes (Hap) for OsNAC42. Box edges represent the 0.25 quantile and 0.75 quantile with the median values shown by bold lines. Whiskers extend to data no more than 1.5 times the interquartile range, and remaining data are indicated by dots. Differences between the haplotypes were analyzed by Welch's t test. c Phenotype of WT (Zhonghua11, ZH11), Tilling mutant (osnac42) and heterozygote (H), bar = 20 cm. d qRT-PCR analysis of OsNPF6.1 of WT (Zhonghua11, ZH11), Tilling mutant (osnac42) and heterozygote (H). Three biological replicates were used for qRT-PCR. e OsNPF6.1 and OsNAC42 transcript levels in different tissues. OsActin1 was used as a control, $n = 3$. f OsNPF6.1 and OsNAC42 expression under HN treatment from 0 to 24 h in leaf (KCl as a control of LN representing nitrogen starvation), $n = 3$. Data are presented as means ± SD. P values (versus the ZH11) were calculated with Student's t test. $^{**}P < 0.01$. The source data underlying (Adopted from Tang et al., 2019)

3.2 Organic-integration fertilization and the promotion of ecological farming

When it comes to sustainable farming, relying solely on chemical fertilizers is probably not a long way off. Many places have begun to try to bring back the "traditional old methods" such as manure, compost and bio-organic fertilizer, and use them together with inorganic fertilizer. The results are really good. Not only can the yield be stabilized, but also the vitality of the soil and the diversity of microorganisms have improved significantly (Iqbal et al., 2021; Urmi et al., 2022). Some studies simply replaced part of the chemical nitrogen source, approximately 30%-50% of the components, and replaced it with organic fertilizer. Not only did the land not become lean, but the fertilizer also lasted longer, and the yield and fertilizer efficiency did not decline. This "mixed and matched" fertilization approach is indeed more in line with the direction of ecological agriculture than a single route. It can also reduce the reliance on synthetic fertilizers and, incidentally, alleviate the problem of environmental degradation.

3.3 Smart fertilization and precision agriculture: emerging trends

Intelligent fertilization sounds quite "high-end and sophisticated", but in fact, it has gradually been implemented. New tools such as remote sensing, AI, and variable fertilization systems have begun to help farmers actually examine the soil, measure nutrients, and apply fertilizers at regular intervals and in fixed quantities (Lu et al., 2020). In this way, less fertilizer was used, up to a quarter could be saved, the efficiency of nitrogen fertilizer increased, but the output did not suffer a loss. More importantly, greenhouse gas emissions can still be reduced significantly. However, this set of operations is by no means simple. Equipment, data and technical training are all indispensable. Farmers also need to adopt them gradually. However, in any case, this route points out a new direction for future rice cultivation - how to achieve high yields does not rely on excessive fertilization, but on smarter application methods.

4 Field Evaluation Indicators of Nitrogen-efficient Rice Varieties

4.1 Growth dynamics and population structure during the growing season

To be honest, whether high-nitrogen-efficiency varieties are good or not, it is not enough to just look at the yield. How they grow in the fields and whether the population structure is stable or not all need to be taken into consideration. Under low-nitrogen conditions, some varieties can still maintain relatively strong root systems, and the biomass of the aboveground part is not bad either. The roots have long density and fast growth rate. However, this effect is sometimes also related to whether the planting density and the amount of nitrogen fertilizer applied are well coordinated. Too low density or too much or too little nitrogen fertilizer may disrupt the rhythm. Generally speaking, moderate nitrogen dosage and reasonable planting density are conducive to dry matter accumulation, an increase in the number of panicles, and a more reasonable leaf area, thereby forming a relatively ideal population structure (Zhu et al., 2023). Some NUE varieties also have good canopies, many tillers, and well-grown flag leaves. Photosynthesis is relatively stable throughout the growing season, and resource conversion keeps up (Li et al., 2024).

4.2 Nitrogen uptake, utilization efficiency, and recovery rate

Absorbing a lot of nitrogen does not necessarily mean it is used well. If nitrogen cannot be recovered, it is still in vain. To truly determine whether a variety is highly efficient or not, it is necessary to look at several aspects including total absorption, utilization rate and recovery rate together. Especially when nitrogen application is reduced, the gap is easier to be seen (Wu et al., 2016; Lu et al., 2020; Wang et al., 2022). Indicators such as NUpE and NUtE are increasingly commonly used in the field nowadays. When viewed together with AE and PFP, they can better evaluate the overall performance. In fact, once the root system performs well, such as having long roots, a large enough root surface area, and strong oxidation capacity, the efficiency of nitrogen absorption and utilization will be easier to improve. Meanwhile, the activity of enzymes, such as nitrate reductase and glutamine synthase, also plays a key role.

4.3 Yield components and their relationship with economic traits

Whether a variety is worth promoting depends on whether it is productive and stable. But where the output comes from, in the final analysis, it still needs to be examined separately. Factors such as the number of spikes, the number of small spikes, the grouting condition and the thousand-grain weight basically determine the quality of the foundation, and these are closely related to the efficiency of nitrogen fertilizer utilization. Interestingly, many high-NUE varieties have seen their yields increase instead of decrease even when nitrogen input is not so high, thanks to the improvement of these structural factors (redistribution during the grouting period also contributes).

Positive correlations can also be found between physiological indicators such as photosynthetic rate, chlorophyll concentration, and flag leaf fluorescence and grain yield. So these traits are not only useful in breeding but also have great reference value for field evaluation. Finally, only those varieties that can balance high yield and high NUE are truly worthy of long-term use in sustainable production as "star varieties".

5 Mechanisms of Fertilizer Regime Effects on Rice Performance

5.1 Regulation of growth and development by nitrogen supply intensity

Whether rice grows well or not, nitrogen supply is an unavoidable factor. Generally speaking, when nitrogen is provided sufficiently, the plants naturally grow taller, have more tillers, larger leaves, and the biomass increases accordingly, and the yield is also guaranteed. But then again, more nitrogen fertilizer is not necessarily better. Excessive application may instead cause problems, such as slow aging of leaves and inadequate filling of panicles, mostly due to hormonal imbalance or decreased activity of certain key enzymes (Chen et al., 2022). When there is less nitrogen, it will definitely affect the growth, the chlorophyll content will also be low, and the yield is likely to drop. But not all varieties are so brittle. Some "fertilizer-saving" ones can withstand low nitrogen and have a relatively strong growth recovery ability (Qi et al., 2025). In addition, not only the amount should be well controlled, but also the application time is crucial. During critical periods such as panicle differentiation, if nitrogen supply is insufficient, it is easy to miss the yield window (Zhang et al., 2025).

5.2 Impact of nitrogen levels on enzyme activity and chlorophyll content

Once the nitrogen supply changes, the alterations in some enzymes and chlorophyll within plants can be immediately observed. The guys that dominate nitrogen metabolism, such as nitrate reductase (NR) and glutamine synthase (GS), as well as GOGAT, are all very sensitive. When there is sufficient nitrogen, the enzyme activity becomes active, the contents of chlorophyll a and b will also increase, and the efficiency of photosynthesis will rise accordingly (Ali et al., 2021; Ullah et al., 2021; Liao et al., 2022). However, don't be too happy too soon. Excessive use of nitrogen not only fails to infinitely increase the photosynthetic rate, but sometimes even causes problems in reverse, such as increased photosuppression or oxidative stress. At this time, plants have to activate the antioxidant defense line, and enzyme activity and energy allocation are all messed up (Kiran et al., 2016; Cisse et al., 2020; Wang et al., 2022). The situation of low nitrogen is also rather complex. Although the chlorophyll and enzyme activities of some varieties decrease, certain antioxidant systems or starch metabolic pathways in the body are more active instead, indicating that they have their own countermeasures.

5.3 Interaction between fertilization methods and soil nitrogen dynamics

How to fertilize also directly affects the movement of nitrogen in the soil. There are significant differences among various methods. In some places, attempts have been made to combine the "old-fashioned methods" such as biochar, manure and straw with modern synthetic fertilizers. The results are quite good. Not only has the organic carbon in the soil increased, but also the availability of nitrogen and the activity of microorganisms have improved. The root system is well-developed, the enzyme activity is more active, and the nitrogen mineralization is faster. From another perspective, applying fertilizer deeper or to the side can also increase the total nitrogen content in the deep soil and stimulate the activity of beneficial microorganisms. However, if the traditional surface application method is used, it may be more conducive to the accumulation of surface carbon (Xie et al., 2025). Some farmers also use nitrification inhibitors or slow-release fertilizers. Long-term use can make the soil condition more stable and the crop yield does not decrease (Tang et al., 2024). Therefore, fertilization is not merely about "quantity" to win. It depends on what the crops need and what the soil lacks. Tailoring to the specific needs is the key.

6 Case Studies: Regional Field Trials

6.1 Fertilizer-variety matching studies in the middle and lower Yangtze River Basin

In the middle and lower reaches of the Yangtze River, it's not the case that the less nitrogen fertilizer there is, the lower the yield will be. The situation is actually not that simple. Many field trials have found that nitrogen-saving varieties (NSV) did not have a decrease in yield after reducing nitrogen fertilizer application by 40%-60% (from the original 300 kg N/ha to 120-180 kg N/ha), and even broke records, while those common varieties could not withstand such a reduction intensity (Wei et al., 2021; Wei et al., 2025). Not only in terms of yield, but also in terms of tillering number, effective tillering rate, and the number of spikers, NSV is more resilient, and even its carbon and nitrogen metabolism is more stable. However, if chemical nitrogen is partially replaced by organic fertilizers (such as cow dung and cake fertilizer), the nitrogen content in the soil can be significantly increased, which is beneficial for maintaining soil vitality in the long term (Wang et al., 2023; Zhou et al., 2024). In addition, some experiments also pointed out that as long as the nitrogen fertilizer dosage is controlled between 180-223 kg N/ha, nitrogen loss and greenhouse gas emissions can be significantly reduced while the yield approaches the maximum value (more than 95%) (Figure 2) (Xu et al., 2025). So, choosing the right variety and combining it with a reasonable fertilizer strategy can not only ensure production but also reduce environmental pressure. This is not just empty talk.

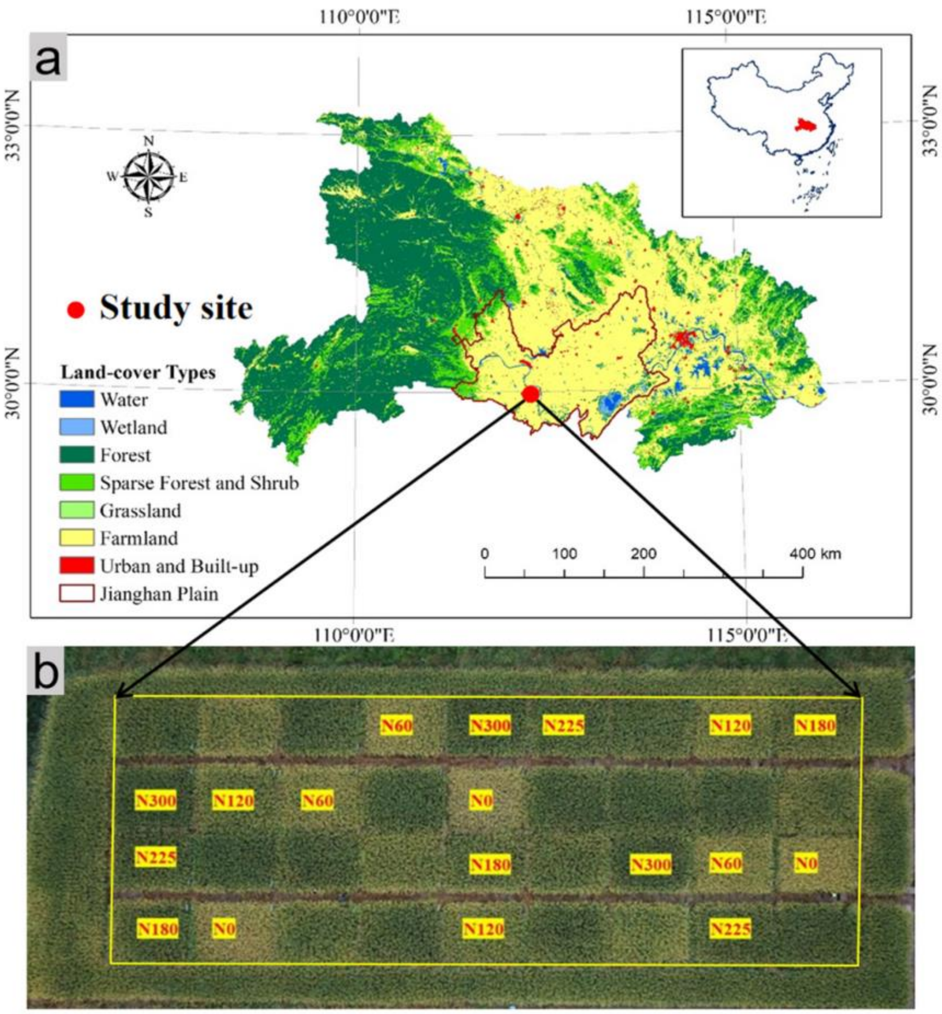

Figure 2 The location of the study area (a) and the layout of the experimental plots (b) (Adopted from Xu et al., 2025)

6.2 Nitrogen reduction practices in major rice production areas of Northeast China

The problem in Northeast China is more often due to "excessive use". The nitrogen fertilizer was heavily applied right from the start, but the output did not increase significantly. Instead, environmental problems emerged first. Recent experiments have offered some more "restrained" approaches, such as controlling the fertilizer application at 99 to 125 kg N/ha, combined with water-saving irrigation or appropriately increasing the planting density. As a result, not only did the harvest index increase, but the grain filling was also better, and the yield actually rose. There is a set of data that is quite illustrative: a 20% reduction in nitrogen fertilizer, a 32% increase in planting density, a 3% to 5% increase in yield, and the quality of the rice is not compromised (Dong et al., 2025). So, in places like Northeast China where "high-starting-point fertilization" is adopted, the way to improve is not just to "apply less", but to "apply less with a plan".

6.3 Nitrogen-saving cultivation models and data analysis in South China's double-cropping areas

In the South China region where double-cropping rice is widely grown, people have long attempted to save nitrogen. The combination of methods like simplified nitrogen reduction cultivation (SNRP), close planting and delayed fertilization has a much more powerful actual effect than traditional approaches. SNRP can increase the yield by 23%, and it is not difficult to double the nitrogen fertilizer utilization rate by two or three times (Fu et al., 2023). There is also the strategy of close planting combined with nitrogen reduction and adding some backward transfer fertilization, which can increase the yield by 24% to 30% and the nitrogen utilization rate by 60% to 70%. Precision fertilization in green fat-rice rotation sounds meticulous, but the results are quite surprising - the amount of synthetic nitrogen used is reduced by one-third to two-thirds, and the nitrogen footprint is also reduced (Liang et al., 2023). From these examples, it can be seen that the key does not lie in relying on a single trick, but in the proper coordination of varieties, fertilizers and planting rhythms, which can enable the double-cropping rice system to achieve a win-win-win situation of "stable yield + high efficiency + low pollution".

7 Integrated Optimization of Variety Selection and Fertilization Strategy

7.1 Developing variety-specific fertilization recommendations

Not all varieties can accept the same fertilization method without exception. Some hybrid rice varieties and high-yield varieties can better exert their potential when the nitrogen fertilizer application rate is controlled within the range of 180 to 225 kg N/ha, combined with water-saving irrigation (Zhu et al., 2024). But it doesn't mean that once the dosage is appropriate, everything else will go smoothly. Different fertilization methods result in different responses of varieties - for instance, some are suitable for deep application, while others perform better under fractional fertilization or controlled-release fertilization (Baral et al., 2020). Salt-tolerant rice varieties are another matter. They are quite sensitive to ammonium nitrogen fertilizers. With an appropriate planting density, their resistance to salt pressure can be further improved. So, to make reliable fertilization suggestions, one cannot merely look at the soil or climate; the variable of genotype must also be taken into account. Without targeted supporting plans, it is hard to talk about green and efficient development.

7.2 Interactions between variety and fertilizer on resource use efficiency

Ultimately, how to apply fertilizer to a variety cannot be decided merely based on experience. The responses of different genotypes to fertilization methods can be described as "vastly different in style". For some varieties, when they are applied with slow-release fertilizers or deep fertilizers, the utilization rate of nitrogen fertilizers can increase sharply, and the yield will also rise accordingly. But with another variety, it might be more "responsive" to foliar spraying or fractional fertilization (Wang et al., 2022; Sajjad et al., 2024). When placed in different irrigation environments, the situation becomes even more complicated - for instance, under alternating dry and wet irrigation or shallow water conditions, some varieties can still achieve a "double improvement" in nitrogen fertilizer efficiency and water use efficiency. These differences are not merely superficial phenomena. Behind them, the mechanisms of crop absorption, transportation and distribution are at work (Lee et al., 2025). So, expecting "one management solution to solve all problems"? Obviously not realistic. To truly enhance the utilization rate of resources, it is necessary to find the "right" combination between varieties and management methods.

7.3 Comprehensive evaluation of high-yield and environment-friendly models

To increase grain production without damaging the environment, relying on a single measure alone is far from enough. From the perspective of field practice, the combination of measures is the right solution - select high NUE varieties, and then combine the methods of controlled-release fertilizer, deep application, and multi-application fertilization. The yield has increased, the quality is guaranteed, and the environmental burden can also be reduced (Zhang et al., 2025). Moreover, this kind of "combined approach" is not only reflected in output efficiency, but also in sustainability. With precise fertilization and water-saving irrigation, even the "invisible" indicators such as soil health and greenhouse gas emissions have been optimized. This model, which takes into account both field management and ecological benefits, is much more reliable than the traditional approach and has laid a relatively stable foundation for sustainable rice production.

8 Conclusions and Prospects

When growing rice in the field, how to apply fertilizer and how to choose the right variety are never two different things. Field observations have found that for some rice varieties with high nitrogen fertilizer utilization rates, after applying slow-release fertilizers, precisely targeted fertilization or deep application, not only has the yield not decreased, but also less nitrogen fertilizer is used, and the land is more worry-free. These "high NUE" varieties are not randomly selected. They rely on genetic screening, breeding strategies, and the identification of some key physiological indicators. Over the years, research on NUE has become increasingly detailed, with a clearer understanding of how genotypes respond to external management, how nitrogen flows within the body, and how to combine genetic advantages with agronomic measures.

However, it's not easy to say. Although the experimental results were good, in reality, there are still not many varieties that can truly promote these highly efficient genes to large-scale cultivation (especially those familiar to farmers). Not to mention, in some places, nitrogen fertilizers are still being used haphazardly, not only wasting resources but also diluting the benefits brought by new varieties. Moreover, soil, climate and varieties vary from region to region. It is basically unrealistic to apply a one-size-fits-all fertilization plan. Moreover, many small-scale farmers lack technology, funds and policies that are not in place. Even if they have good plans, it is difficult for them to implement them.

What needs to be done in the future is actually very clear. On the one hand, it relies on technology, such as through high-throughput phenotyping and multi-omics techniques, to figure out exactly how nitrogen functions in crops. On the one hand, breeding is still necessary to select varieties that are high-yielding, have low nitrogen tolerance, and can also withstand some climatic disturbances. At the same time, one cannot rely solely on general experience. Fertilization strategies should be tailored to different regions and varieties to be more precise. Furthermore, it is necessary to integrate water-saving irrigation, efficient nutrient utilization and digital management methods. Of course, policies should not be absent either - farmers should be encouraged to use less nitrogen, better technologies, and access promotion services and digital tools. Only in this way can the goals of high output, low emissions and risk resistance be truly achieved together.

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Conflict of Interest Disclosure

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

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