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Deep learning-based response mechanism of nitrogen utilization, yield, and quality in mulched drip irrigation rice to nitrogen application rate

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ABSTRACT

Nitrogen management is critical for coordinating productivity, grain quality, and environmental sustainability in film-mulched drip-irrigated rice systems. A 3a field experiment was conducted in Ningxia, Northwest China, to investigate the nonlinear responses of soil nitrogen dynamics, nitrogen use efficiency (NUE), yield formation, and grain quality to different nitrogen application rates under film-mulched drip irrigation (FMDI). Based on the experimental dataset, deep learning models including Deep Neural Network (DNN), Multilayer Perceptron (MLP), Convolutional Neural Network (CNN), and Transformer were employed to characterize complex agronomic response patterns under varying nitrogen conditions. The results showed that increasing nitrogen application significantly enhanced total nitrogen accumulation in deeper soil layers, suggesting potential downward redistribution of nitrogen under excessive nitrogen input. Agronomic traits including plant height, dry matter accumulation, filled-grain ratio, and 1000-grain weight generally increased with nitrogen application. NUE indicators improved under moderate nitrogen conditions but declined substantially when nitrogen application exceeded 180 kg ha^{-1}, indicating diminishing nitrogen utilization efficiency under excessive input. Grain quality responses exhibited clear trade-off characteristics: moderate nitrogen application improved protein accumulation and milling quality, whereas excessive nitrogen increased chalkiness and negatively affected eating-quality-related traits. Model comparison and robustness analyses further demonstrated that deep learning models outperformed conventional linear regression approaches in capturing nonlinear coupling relationships among soil nitrogen, NUE, yield components, and grain quality variables. Comprehensive evaluation suggested that 180 kg ha^{-1} represented the most balanced nitrogen application level for coordinating productivity, grain quality, nitrogen utilization, and environmental sustainability under the arid climatic and alkaline soil conditions of the Ningxia irrigation region. These findings provide scientific support for optimized nitrogen management and coordinated water-fertilizer regulation in FMDI rice production systems.

1. Introduction

Rice is one of the most important staple food crops worldwide, and its stable production is closely associated with global food security and agricultural sustainability (Zhang et al., 2021; Hua et al., 2015). In arid and semi-arid regions, however, conventional flooded rice cultivation is increasingly constrained by water scarcity and low irrigation efficiency (Ebstu and Muluneh, 2025). Film-mulched drip irrigation (FMDI) has emerged as an effective water-saving cultivation technology by integrating drip irrigation with plastic film mulching, thereby improving water distribution, reducing non-productive evaporation, and enhancing soil hydrothermal conditions (Gao et al., 2025a; Zhao et al., 2025; Wang et al., 2023a). Previous studies have demonstrated that FMDI can substantially improve water productivity and maintain rice yield under limited water conditions (Wang et al., 2023b, 2021). Consequently, this technology has attracted increasing attention in water-deficient rice-growing regions.

Ningxia, located in northwestern China, is a typical arid irrigation region and an important high-quality rice production area (Zhang et al.,

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2025; Tang et al., 2010). However, traditional flood irrigation in this region is characterized by high water consumption and risks of secondary soil salinization (Li et al., 2013; Xiong et al., 1996). Under these conditions, FMDI provides an alternative cultivation strategy that can simultaneously reduce irrigation water use and improve soil environmental conditions. Nevertheless, nitrogen management remains a major challenge in FMDI rice systems (Sekiya et al., 2025; Khan et al., 2023; Shen et al., 2016). Nitrogen fertilizer is essential for rice growth, biomass accumulation, grain formation, and quality development (Gao et al., 2025b; Jiang et al., 2022), but excessive nitrogen application may reduce nitrogen use efficiency (NUE), accelerate nitrogen leaching, and negatively affect grain quality and soil sustainability (Wu et al., 2026; Hameed et al., 2026; Xu et al., 2025). Therefore, optimizing nitrogen application under FMDI conditions is critical for achieving coordinated improvement in yield, quality, and environmental performance.

Previous studies have extensively investigated the effects of nitrogen application on rice yield formation, NUE, and grain quality. Existing evidence indicates that appropriate nitrogen supply can enhance biomass accumulation, photosynthetic capacity, grain filling, and protein synthesis, thereby improving rice productivity and quality (Song et al., 2025; Kashiwagi, 2021; Zhou et al., 2018). However, excessive nitrogen input may promote soil nitrogen accumulation, reduce nitrogen utilization efficiency, and induce trade-offs among different quality traits (Ma et al., 2026; Fu et al., 2025; Zhou et al., 2021a). Although these studies provide important insights into nitrogen regulation in rice cultivation, most of them focus on individual traits or single processes, such as yield response or quality formation, rather than considering the integrated responses of soil nitrogen dynamics, NUE, yield components, and grain quality within the soilplant system (Liu et al., 2023; Zahra et al., 2022; Lee, 2021). In addition, conventional statistical approaches, including correlation analysis and regression models, often have limited capability in capturing the nonlinear interactions and coupled responses among multiple agronomic variables under different nitrogen conditions (Tang et al., 2025; Zhang et al., 2024).

Recent advances in artificial intelligence and deep learning provide new opportunities for analyzing complex agricultural systems. Deep learning models, such as Deep Neural Networks (DNN), Multilayer Perceptrons (MLP), Convolutional Neural Networks (CNN), and Transformers, have shown strong capabilities in nonlinear feature extraction and pattern recognition in agricultural applications, including crop growth monitoring and yield prediction (Zhang et al., 2026; Li et al., 2025; Wang et al., 2025; Yamaguchi et al., 2025; Han et al., 2022). Nevertheless, current applications of deep learning in rice studies are mainly prediction-oriented and primarily focus on yield estimation or image classification, while limited attention has been paid to interpreting agronomic response pathways and identifying nitrogen regulation thresholds in field management systems (Duc et al., 2025; Zheng et al., 2022). Consequently, the nonlinear response mechanisms linking nitrogen application, soil nitrogen distribution, NUE, yield formation, and grain quality under FMDI conditions remain insufficiently understood (Guo et al., 2026, 2023).

Although previous studies have investigated nitrogen effects on rice yield, nitrogen use efficiency, or grain quality under FMDI systems, most focused on isolated agronomic responses or linear statistical relationships (Proud et al., 2023; Yan et al., 2022; Guo et al., 2021). The integrated responses and nonlinear trade-offs among soil nitrogen dynamics, nitrogen utilization, yield formation, and grain quality remain poorly understood, particularly under arid irrigation conditions. In addition, conventional regression approaches have limited capability in capturing complex coupling relationships among multiple agronomic variables. Therefore, a three-year field experiment was conducted in Ningxia, China, to investigate the effects of nitrogen application on rice performance under film-mulched drip irrigation. The objectives of this study were to: (1) quantify the responses of soil nitrogen distribution, nitrogen use efficiency, yield components, and grain quality to different nitrogen application rates; (2) identify the critical nitrogen threshold balancing productivity, quality, and nitrogen utilization; and (3) explore the nonlinear response relationships among nitrogen application, crop growth, and quality traits using deep learning models. The novelty of this study lies in integrating soil nitrogen dynamics, NUE, yield formation, and grain quality into a unified analytical framework, while applying interpretable deep learning approaches to reveal nonlinear agronomic responses under FMDI conditions. The findings provide theoretical support for precision nitrogen management and sustainable rice production in arid irrigation regions.

2. Materials and methods

2.1. Field experiment

The experimental site was located in Luhua Town, Xixia District, Yinchuan City, Ningxia (38°26′N, 106°03′E; elevation 1120 m) (Fig. 1). This region is characterized by an arid to semi-arid climate, with an annual mean temperature of 9.87 ℃, an average annual precipitation of 192.5 mm, of which 62.3% falls between June and August, and an annual evaporation of 1953.7 mm, which is 10.12 times of the average annual precipitation.

The field experiment was conducted continuously for three years (2017–2019). To eliminate the potential effects of repeated tillage and maintain uniform initial soil conditions, the experimental plots were shifted by 50 m each year within the same area. The test soil was all classified as silty clay loam under flood irrigation, and the main initial soil physicochemical properties before sowing are shown in Table 1. The rice variety used in the experiment was Ningjing 43, a high-quality cultivar developed locally in Ningxia. It is a japonica-type, late-maturing variety with a growth duration of approximately 155 days, exhibiting strong lodging resistance, high fertilizer tolerance, cold tolerance, and good disease resistance.

2.2. Experiment scheme design

The experiment adopted a randomized block design in the field with a comparative treatment approach, using plots of 4 m × 10 m, each replicated three times. Row spacing was 30 cm, hill spacing was 20 cm, and 20 seeds were sown per hill. In all three years, sowing occurred in early May, seedling emergence in late May, and yield measurement and harvest in early October. Water-saving irrigation was implemented in the experimental field, with groundwater pumped from the site used as the water source. After sediment filtration by the head control unit, irrigation was applied through φ16 in-line drip tapes with a dripper spacing of 20 cm and an emitter discharge of 2 L/h, with one drip tape installed between every two rice rows. Soil moisture in the planned wetting zone of the rice root layer was used as the irrigation control index. The upper irrigation limit was set at soil saturation, and the lower limit at 85% of saturation. When soil moisture dropped below or approached the lower limit, drip irrigation was applied until the upper limit was reached to maintain soil moisture near saturation. The nitrogen fertilizer used was water-soluble urea (46–0–0), with 60% applied as basal fertilizer at sowing and 40% applied through drip fertigation during different growth stages.

The nitrogen application rates were determined according to the *Recommendation Manual for Formula Fertilization of Major Crops in Ningxia*, compiled by the Ningxia Agricultural Technology Extension Station. This manual provides region-specific recommendations regarding fertilizer type, application rate, timing, and management practices for major crops under different target yield levels and is widely adopted by local farmers in the Ningxia irrigation region. In the present study, the fertilization scheme recommended in the *Formula Fertilization Recommendation Card for Water-Saving Irrigated Rice* was selected as the standard nitrogen application level (180 kg/ha). Based on this recommended rate and local farming practices, additional nitrogen treatments were carried out at 30%, 60%, 90% were established to represent

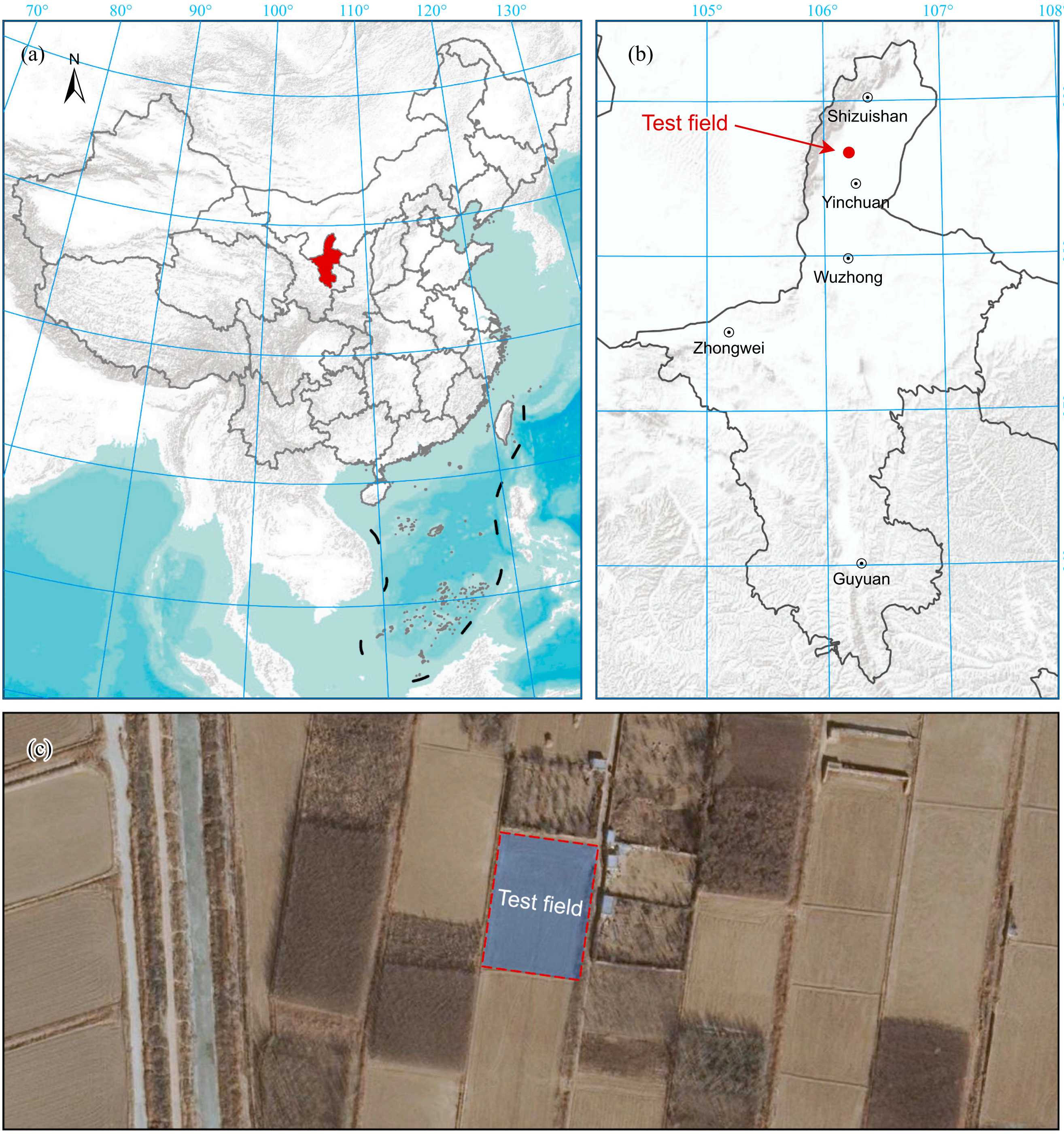

Fig. 1. Location of experiment site. (a) Location of Ningxia in China; (b) Location of the experiment site in Ningxia; (c) Satellite image of the experiment site.

deficient, moderate, and excessive nitrogen supply conditions. Based on this, four nitrogen application rates were established—60 kg/ha (N1), 120 kg/ha (N2), 180 kg/ha (N3), and 240 kg/ha (N4)—with a no-nitrogen treatment (N0) as the control. Phosphorus fertilizer (superphosphate, P_2O_5 90 kg/ha) and potassium fertilizer (potassium oxide, K_2O 180 kg/ha) were entirely applied at sowing, and all other field management practices were kept consistent across treatments.

2.3. Data collection

2.3.1. Soil parameter monitoring

Before sowing and fertilization, soil samples were collected from different soil layers (0–20, 20–40, and 40–60 cm) using a soil auger to determine the basic physicochemical properties of the experimental field. During the rice growth period, soil samples were periodically collected after major growth stages and at maturity to analyze total nitrogen distribution within the soil profile. All soil samples were air-dried, ground, and passed through a 2-mm sieve prior to analysis. Soil total nitrogen content was determined using the Kjeldahl digestion method.

2.3.2. Irrigation flow monitoring

During the rice growth period, soil moisture content was monitored twice daily (07:00 and 18:00) using a TPIME-PICO soil moisture meter. Measurements were conducted at representative sampling points within each treatment plot to monitor soil water dynamics under film-mulched

Table 1
Basic properties of tested soils at 0–60 cm.

Years	Organic matter ($g\bullet kg^{-1}$)	Total nitrogen ($g\bullet kg^{-1}$)	Alkali-hydrolysable N ($mg\bullet kg^{-1}$)	Available P ($mg\bullet kg^{-1}$)	Available K ($mg\bullet kg^{-1}$)
2017	1.46	0.62	52.7	9.6	155.2
2018	1.47	0.59	53.4	9.7	156.0
2019	1.43	0.57	52.1	9.7	153.7
Years	Soluble salts ($g\bullet kg^{-1}$)	pH value	Soil density ($g\bullet cm^{-3}$)	Field capacity (%)	Texture
2017	0.96	8.4	1.41	21.7	Heavy loam
2018	0.97	8.6	1.43	21.2	Heavy loam
2019	0.91	8.2	1.42	21.5	Heavy loam

drip irrigation conditions. Irrigation amounts and irrigation frequency were recorded throughout the experimental period according to field management practices.

2.3.3. Nitrogen utilization efficiency

At rice maturity, three representative tagged plants were collected, air-dried, weighed, and ground, passed through a 0.18 mm sieve, digested with concentrated H_2SO_4–H_2O_2, and analyzed for nitrogen content using a Kjeldahl apparatus, after which nitrogen-use–related indices were calculated.

$$\text{Nitrogenagronomicefficiency} = \frac{(\text{Theyieldofnitrogentreatment} - \text{Theyieldofnon-nitrogentreatment})}{\text{Nitrogenapplicationrate}} \times 100\%$$

$$\text{Nitrogenrecoveryefficiency} = \frac{\left(\begin{array}{l}\text{Nitrogenuptakeoftheovergroundpartsofnitrogentreatment}\\ -\text{Nitrogenuptakeoftheovergroundpartsofnon-nitrogentreatment}\end{array}\right)}{\text{Nitrogenapplicationrate}} \times 100\%$$

$$\text{Nitrogenphysiologicalefficiency} = \frac{(\text{Theyieldofnitrogentreatment} - \text{Theyieldofnon-nitrogentreatment})}{\left(\begin{array}{l}\text{Nitrogenuptakeoftheovergroundpartsofnitrogentreatment}\\ -\text{Nitrogenuptakeoftheovergroundpartsofnon-nitrogentreatment}\end{array}\right)} \times 100\%$$

$$\text{Nitrogenpartialfactorproductivity} = \frac{(\text{Theyieldofnitrogentreatment})}{\text{Nitrogenapplicationrate}} \times 100\%$$

2.3.4. The yield and quality of rice

After rice maturity, three sets of samples were collected from three different positions within each treatment plot. After natural air-drying, the samples were hand-threshed, and straw height, straw dry weight, thousand-grain weight, number of filled grains, and number of unfilled grains were recorded to calculate the filled-grain ratio.

After threshing, samples were stored indoors for quality analysis. They were milled into first-grade standard rice according to the Chinese standard (GB/T 1354–2018) and subjected to component testing. Rice quality evaluation criteria are shown in Table 2.

Table 2
Rice quality test standard.

Items	Standards	Items	Standards
Chalky grain rate	GB/T17891–1999	Head rice rate	GB/T 21719–2008
Chalkiness degree	GB/T17891–1999	Amylose content	GB/T15683–2008
Length-width ratio	GB/T17891–1999	Gel consistency	GB/T22294–2008
Unsound kernel	GB/T 5494–2008	Protein content	GB/T5511–2008
Brown rice rate	GB/T 5495–2008	Rice sensory evaluation	GB/T15682–2008

2.4. Deep learning (DL) modeling framework

To analyze the nonlinear responses of soil nitrogen dynamics, nitrogen use efficiency (NUE), yield formation, and grain quality to nitrogen application under film-mulched drip irrigation, four deep learning models were developed, including Deep Neural Network (DNN), Multilayer Perceptron (MLP), Convolutional Neural Network (CNN), and Transformer. These models were selected because of their different capabilities in nonlinear regression, feature extraction, and global dependency learning, enabling comprehensive comparison of model performance and response characterization.

The input variables included nitrogen application rate, soil depth, experimental year, and measured agronomic indicators, while the output variables consisted of soil total nitrogen content, NUE-related indices, yield components, and rice quality traits. Prior to model training, all variables were normalized using Z-score standardization to eliminate dimensional differences among indicators.

The dataset was constructed from a three-year field experiment with five nitrogen treatments, three replicates per treatment, and multiple observations for each indicator, resulting in 315 samples per variable. The dataset was randomly divided into training and validation sets at a ratio of 80:20 while maintaining consistency in treatment distribution and interannual representation between subsets.

The MLP model was used as a baseline nonlinear regression model because of its relatively simple fully connected architecture and stable performance on structured agricultural datasets. The DNN model extended the MLP framework by introducing multiple hidden layers to improve deep nonlinear feature extraction. The CNN model was employed to capture local response characteristics and interactions among agronomic variables through convolution operations and weight sharing. The Transformer model was introduced to quantify global dependencies among variables using a self-attention mechanism, thereby improving the representation of coupled nonlinear relationships among nitrogen application, crop growth, and quality indicators.

All models were implemented using the TensorFlow framework. Mean squared error (MSE) was adopted as the loss function, and the Adam optimizer was used for parameter optimization

with an initial learning rate of 0.001. The batch size and epoch number were set to 32 and 100, respectively. Early stopping was applied during training to prevent overfitting, where training was terminated if validation loss did not decrease for 10 consecutive epochs.

To improve model robustness and reduce uncertainty caused by random data partitioning, five-fold cross-validation was further conducted on the training dataset. The average results of the five validation runs were used as the final model performance metrics.

In addition to prediction accuracy evaluation, feature-response relationships were analyzed using model response curves and marginal effect analysis to identify critical nitrogen thresholds and nonlinear response characteristics of rice growth, nitrogen utilization, and grain quality under different nitrogen application conditions.

2.5. Evaluation criterion

To evaluate model performance, the coefficient of determination (R^2), root mean squared error (RMSE), and mean absolute error (MAE) were employed. R^2 represents the extent to which the model captures the variability in the data, while RMSE assesses the accuracy of the model predictions. MAE serves as an indicator of the model's predictive performance by reflecting the average magnitude of prediction errors. The formulas for these evaluation metrics are as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{m}(y_i - \overline{y})(x_i - \overline{x})\right]^2}{\sum_{i=1}^{m}(y_i - \overline{y})^2 \sum_{i=1}^{m}(x_i - \overline{x})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \quad (2)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{m}|x_i - y_i| \quad (3)$$

Where n is the number of observations; i denotes the index of the calculated sample, ranging from 1 to n; x_i and y_i represent the estimated value and the observed value on the day i, respectively; and denote the mean values of x_i and y_i, respectively.

3. Results and analysis

3.1. Analysis of field experiment results

3.1.1. Effects of different nitrogen application rates on total nitrogen content

The total nitrogen content in the soil is directly affected by the nitrogen application rate (Fig. 2). The experimental results indicate that, within the same soil layer across different years, soil total nitrogen content increases significantly with higher nitrogen application rates. As the primary cultivation layer in rice fields, the 0–20 cm soil layer shows a pronounced increase in total nitrogen content with increasing nitrogen application, with stable interannual variation. From 2017–2019, the total nitrogen content in the cultivation layer under all nitrogen treatments exceeded that of the control (N0), with the highest values observed for the N4 treatment (240 kg/ha). Compared with the N0 treatment, the average increases in cultivation-layer total nitrogen content under N1, N2, N3, and N4 treatments were 2.5%, 8.4%, 10.7%, and 11.7%, respectively. When the nitrogen application exceeded 180 kg/ha, the increase in total nitrogen content in the cultivation layer tended to level off, suggesting a threshold effect in the nitrogen retention capacity of this soil layer. Across all treatments, soil total nitrogen content exhibited a decreasing vertical pattern with increasing soil depth, with the highest values in the 0–20 cm layer, followed by the 20–40 cm layer, and the lowest in the 40–60 cm layer. High nitrogen treatments (N3 and N4) exerted the strongest effect on increasing total nitrogen content in deeper soil layers (40–60 cm). Under N4, the total nitrogen content in the 40–60 cm layer increased by 58.5% compared with N0 substantially higher than the increase observed in the cultivation layer - indicating that excessive nitrogen application facilitates nitrogen migration to deeper soil layers.

3.1.2. Effects of different nitrogen application rates on nitrogen utilization in Rice

Significant differences in nitrogen use efficiency were observed under different nitrogen application rates (Fig. 3). Aboveground nitrogen uptake increased initially and then stabilized with increasing nitrogen application, reaching its peak at 180 kg/ha, which was 36.9% higher than that of the no-nitrogen control (N0). When the application rate was further increased to 240 kg/ha, nitrogen uptake showed a slight decline. The four nitrogen use efficiency indicators exhibited similar response patterns. Within the application range of 0–180 kg/ha, agronomic efficiency (from 34.81% to 38.77%), uptake efficiency (from 44.38 g/g to 48.15 g/g), physiological efficiency (from 74.64 g/g to 86.03 g/g), and partial factor productivity (from 90.66 g/g to 97.57 g/g) all increased continuously with greater nitrogen input. When nitrogen application exceeded 180 kg/ha, all efficiency indicators showed a significant declining trend, with the 240 kg/ha treatment displaying an average reduction of 4.2% compared with the 180 kg/ha treatment. Among the different nitrogen levels, the N3 treatment (180 kg/ha) achieved the highest values across all indicators, surpassing N1, N2, and N4. This indicates that increasing nitrogen application enhances overall nitrogen use efficiency when applied below 180 kg/ha, whereas rates exceeding this threshold result in inefficient uptake and reflect nitrogen over-application.

3.1.3. Effects of different nitrogen application rates on rice yield composition

Nitrogen application rates modify rice canopy structure and biomass allocation, thereby directly or indirectly affecting the formation of yield components and ultimately determining final yield. Under different nitrogen application levels, rice yield components exhibit a distinct stepwise increasing trend, and the responsiveness of each component to nitrogen input varies markedly (Fig. 4). As nitrogen application increases, rice culm height, culm dry weight, filled grain ratio, and thousand-grain weight all show upward trends. Culm height and culm dry weight, as indicators of vegetative growth, increase linearly and steadily with higher nitrogen rates; from N0 to N4, culm height rises by 11.0% and culm dry weight by 5.9%, with culm height showing greater sensitivity to nitrogen. The filled grain ratio, a key indicator of reproductive growth, is strongly and positively correlated with nitrogen application ($r = 0.88$), increasing by 7.1% from N0 to N4, with the fastest growth under medium-nitrogen levels (N2~N3), and is highly associated with culm dry weight ($r = 0.91$). Thousand-grain weight responds weakly to nitrogen, with only a 1.0% increase from N0 to N4. Overall, medium nitrogen levels (120–180 kg/ha) constitute the optimal range for balancing yield performance and nitrogen-use efficiency.

3.1.4. Effects of different nitrogen rates on rice quality

Rice quality significantly affects the promotion of rice cultivation and its commercial value, and both domestic and international researchers have paid considerable attention to grain quality，With rapid global economic development and rising living standards, it has become essential to pursue superior appearance, texture, and taste in rice, beyond high yield and quality. For high-quality rice, the quality standard is a composite trait. Based on extensive studies, rice quality is

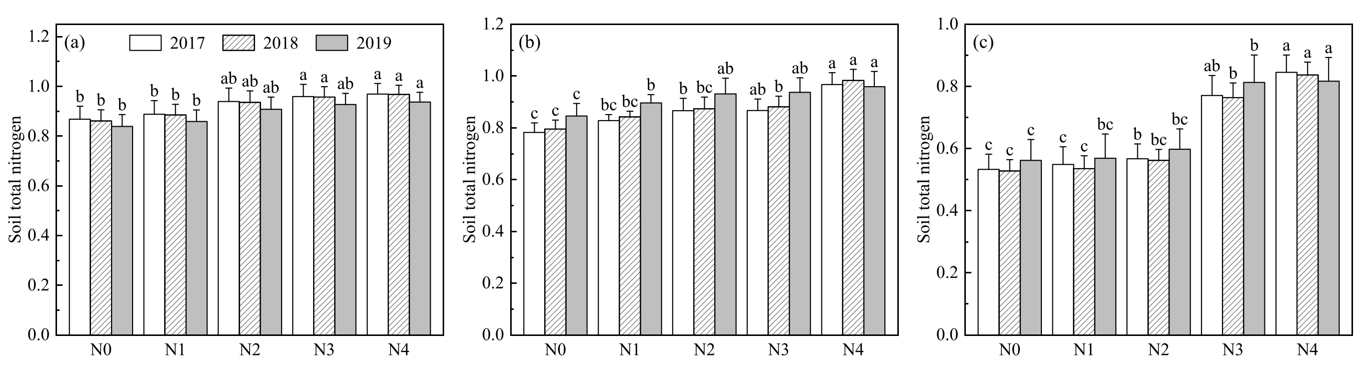

Fig. 2. The total nitrogen content in the 0–60 cm soil layer.

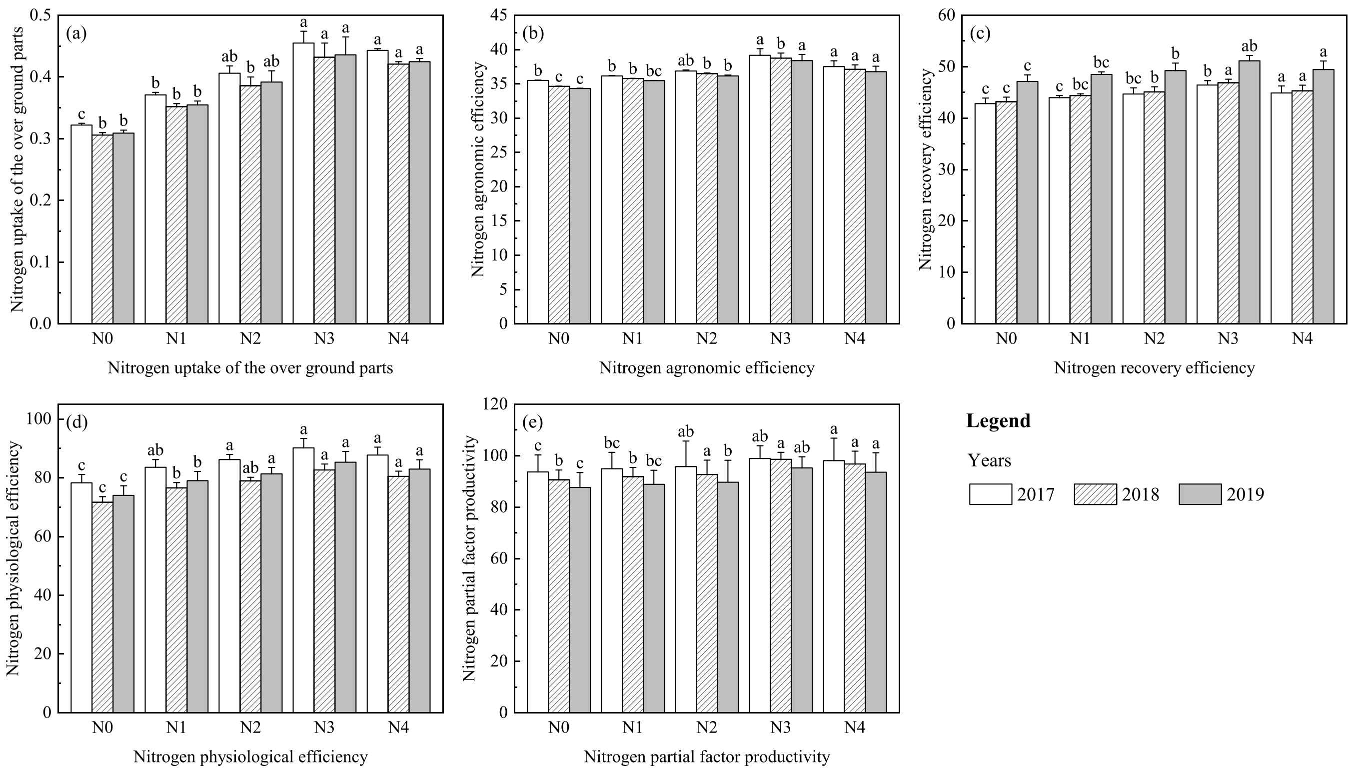

Fig. 3. Nitrogen fertilizer utilization of rice under different treatments.

primarily reflected by four categories of indicators: milling quality, appearance quality, physicochemical quality, and eating quality. Milling quality mainly includes brown rice rate, milled rice rate, and head rice rate; appearance quality is primarily reflected by chalkiness degree, chalky rice rate, imperfect grains, and grain length-to-width ratio; physicochemical quality mainly comprises amylose content, gel consistency, and protein content; eating quality is evaluated based on sensory scores of cooked rice. The average differences in rice quality across different treatments over three years are shown in Fig. 5.

Brown rice rate refers to the percentage of the total weight of fully filled brown rice grains plus half the weight of imperfect grains after dehusking, and it is a standard parameter for rice pricing. Studies have shown that rice grains that are mature, plump, and have thinner husks exhibit higher brown rice rates. Milled rice refers to brown rice that has been polished to meet the third-grade Chinese standard (GB1354), with grain lengths reaching at least three-quarters of the average length of intact grains. Head rice rate is defined as the percentage of milled rice relative to the weight of the clean rice sample. With increasing nitrogen application, the main milling quality indicators initially increase and then decrease. The brown rice rate peaks at 84.348% under 120 kg/ha (N2), while the milled rice rate and head rice rate reach maximum values of 75.286% and 64.868% under 180 kg/ha (N3), representing increases of 2.41% and 6.17% compared with the control (N0), followed by slight declines with further nitrogen increase. The increases in milling quality under the N4 treatment were lower than those under N3, indicating that while nitrogen application can enhance key milling quality indicators, excessive nitrogen may exert inhibitory effects.

Chalkiness is considered an undesirable quality trait, representing a structural defect in rice grains. Chalkiness not only affects the visual appearance of rice but also its processing quality. Rice chalkiness refers to the white, loose, and opaque regions within the endosperm, serving as an important indicator of rice quality and affecting appearance, commercial value, and processing performance. The chalky portion in rice results from insufficiently compact accumulation of starch and protein granules in the endosperm, making the grains more prone to breakage during processing. Chalkiness degree is defined as the proportion of chalky area to the total surface area of the grain, while chalky rice rate refers to the proportion of chalky grains within a unit sample. Previous studies have shown a significant correlation between chalkiness degree and chalky rice rate, with higher chalkiness degrees corresponding to higher chalky rice rates; these indicators are influenced by rice variety and cultivation environment. Nitrogen application rates have a pronounced effect on the occurrence of imperfect grains in rice. Under different nitrogen treatments, rice chalkiness degree and chalky rice rate consistently increased with nitrogen application, rising from 2.612% and 0.536% in N0–2.705% and 0.654% in N4, representing total increases of 3.56% and 22.01%, respectively. This indicates that nitrogen application promotes chalkiness degree and chalky rice rate, likely because higher nitrogen accelerates grain filling, which can impede the accumulation of nutrients in the grain, resulting in poorly filled grains, higher chalkiness, and lower endosperm transparency. Quality results further show that with increasing nitrogen application, both grain length-to-width ratio and the proportion of imperfect grains decrease significantly; imperfect grains exhibited the most pronounced decline, reducing by 27.34% from N0 to N4, while length-to-width ratio decreased from 1.765 to 1.724.

The amylose content of rice is closely related to its cooking and physicochemical properties, affecting the stickiness and softness of cooked rice and significantly influencing its texture and palatability. Regarding the effect of nitrogen application on rice amylose content, results are inconsistent among studies; some report a gradual decrease in amylose with higher nitrogen, others indicate that amylose content is insensitive to nitrogen, while some suggest that amylose increases with nitrogen application. Under different nitrogen treatments, amylose content and gel consistency initially increased and then decreased with increasing nitrogen, reaching maximum values of 17.365% and 72.054% at N3, respectively, whereas protein content and sensory scores of cooked rice continued to increase with nitrogen, reaching 8.992% and 79.364% at N4, representing increases of 4.06% and 3.84% compared to N0. In this study, amylose content showed a slight increase

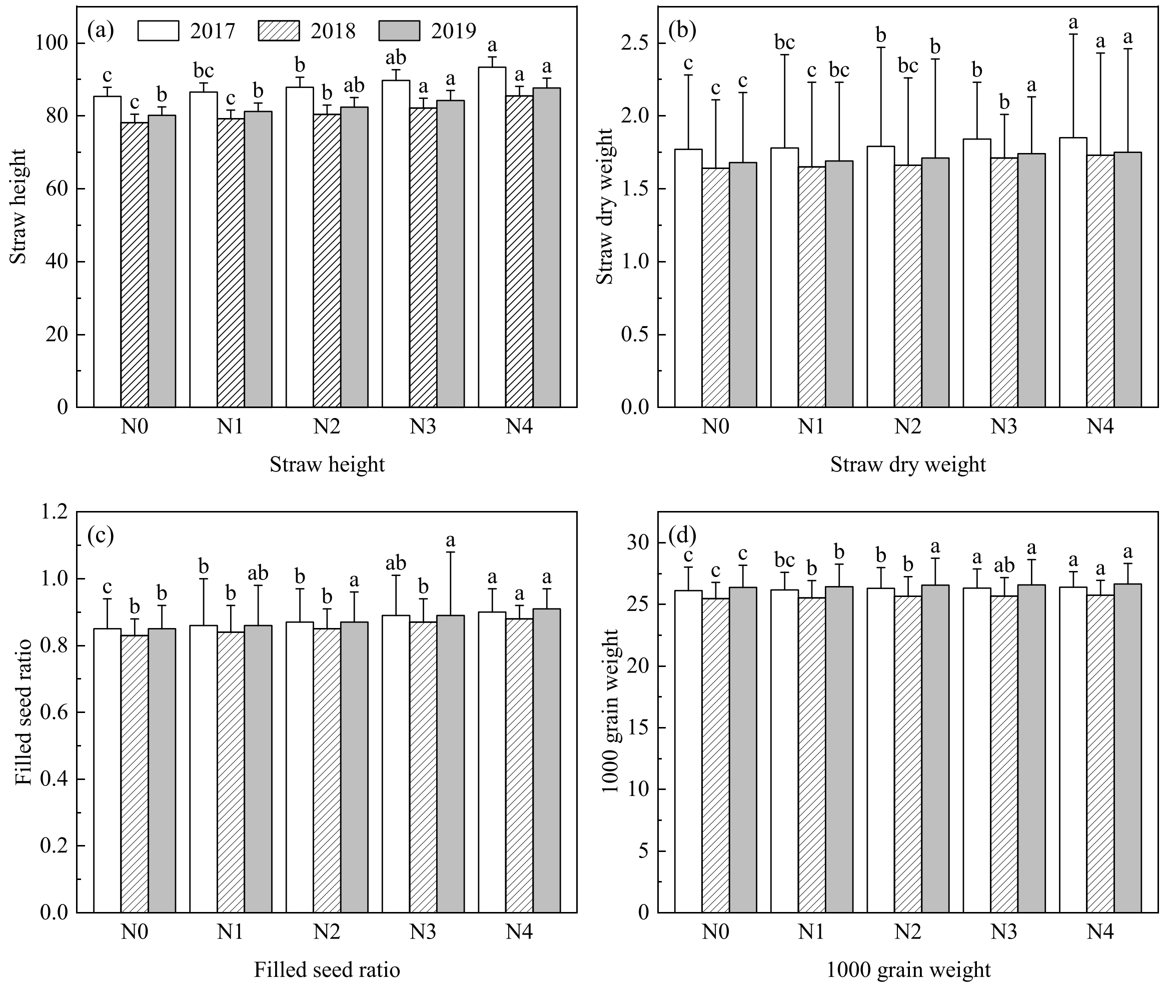

Fig. 4. The biological characteristics of rice under different treatments.

with nitrogen application, but the magnitude was small and differences among treatments were not significant, indicating that nitrogen had no substantial effect on amylose content. This variety is classified as a low-amylose type, with starch content primarily controlled by genetic factors.

3.2. Model calibration and validation

The field experiment was conducted over three years, with five treatments each year, three replicates per treatment, and seven samples per plot, resulting in 315 observations per indicator, all of which were calibrated. After verifying the completeness of the raw data and confirming no missing values, Z-score normalization was applied to each indicator to eliminate dimensional differences that could affect model training. The dataset was randomly split into training and validation sets at an 80:20 ratio, ensuring consistency in treatment types and year distribution between the two sets. Mean squared error (MSE) was used as the loss function, and the Adam optimizer was employed for parameter updates, with a learning rate of 0.001, batch size of 32, and 100 epochs. Early stopping was applied during training, halting model training if the validation loss did not decrease for 10 consecutive epochs, to prevent overfitting. Additionally, to enhance model stability, five-fold cross-validation was performed on the training set, and the average of the five cross-validation results was used as the final calibration parameter.

Scatter plots comparing simulated and observed values were used to assess the model's predictive accuracy for various indicators (Fig. 6). The model captured soil nitrogen dynamics across different soil layers (0–60 cm) effectively. For crop nitrogen utilization, indicators such as aboveground nitrogen uptake, nitrogen recovery efficiency, and physiological nitrogen use efficiency showed very high simulation accuracy. Regarding crop growth and yield traits, simulations of filled grain ratio, thousand-grain weight, and culm height also demonstrated good reliability. In all figures, training and validation sets closely followed the perfect prediction line, and combined with R^2, RMSE, and MAE metrics, the model exhibited excellent overall accuracy in simulating soil nitrogen, crop nitrogen utilization, and growth and yield traits.

3.3. Performance evaluation and robustness analysis

To evaluate the predictive reliability of the employed deep learning models, conventional multiple linear regression (MLR) models were introduced as baseline models for comparison. The DNN model was applied to soil total nitrogen dynamics, the MLP model to nitrogen use efficiency (NUE) indicators, the CNN model to yield components, and the Transformer model to grain quality traits. Model performance was assessed using the coefficient of determination (R^2) and root mean square error (RMSE). In addition, repeated 5-fold cross-validation was conducted to evaluate robustness and uncertainty, and means ́standard deviation of R^2 and RMSE across folds were reported.

The results indicated that all deep learning models consistently outperformed the baseline MLR models across different agronomic tasks (Table 1). For soil nitrogen, the DNN model captured multilayer nonlinear patterns more effectively than MLR. For NUE, the MLP model exhibited higher predictive accuracy and lower RMSE. The CNN model showed superior performance in predicting yield components, whereas

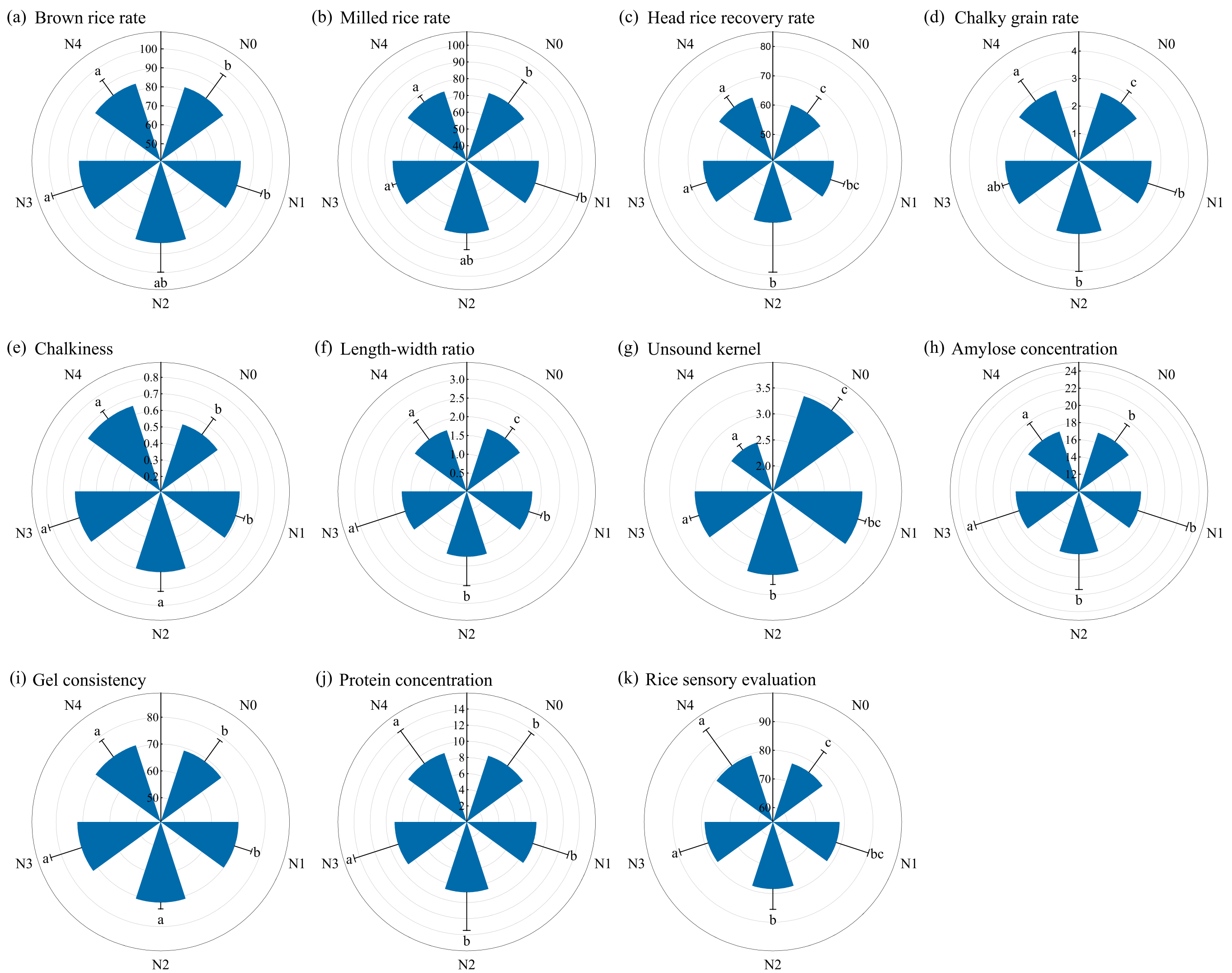

Fig. 5. The average difference in rice quality under different treatments.

the Transformer model achieved the highest R^2 for grain quality traits, reflecting its ability to capture complex dependencies among multiple quality indicators. Repeated cross-validation demonstrated relatively low variation across folds, indicating acceptable robustness and stability of the models under the current experimental conditions.

3.4. Response mechanism of nitrogen utilization, yield, and quality

3.4.1. Response of total nitrogen content to nitrogen application rate

With increasing nitrogen application, total soil nitrogen content generally increased, although the response varied across different soil layers (Fig. 7). Compared with the control (N0), all nitrogen treatments significantly increased total soil nitrogen content. The N4 treatment showed the highest overall increase of 28.8%, with the most pronounced enhancement observed in the 40–60 cm soil layer. The N3 treatment achieved an overall increase of 22.1%, with the most consistent improvement in the 0–20 cm topsoil layer. The N2 treatment exhibited an overall increase of 8.3%, representing a relatively cost-effective option. The N1 treatment showed a modest overall increase of 3.4%, indicating a relatively limited effect.

Analysis of the slopes of the response curves indicated that all treatments in the 0–20 cm topsoil showed a decreasing trend, with greater decreases observed at higher nitrogen levels, suggesting more vigorous crop nitrogen uptake under high nitrogen conditions. In the 20–40 cm layer, all treatments except N4 exhibited an increasing trend, with the N3 treatment showing the most pronounced rise. In 40–60 cm layer, treatments N0-N3 showed an increasing trend, whereas N4 displayed a decreasing trend, indicating that excessive nitrogen application may lead to leaching of deep-layer nitrogen.

The interaction coefficient between nitrogen application and soil depth reflects the combined effect on total soil nitrogen content, with the highest coefficient observed in the 40–60 cm layer, indicating that deep soil nitrogen is most sensitive to nitrogen application; the 20–40 cm layer showed a moderate coefficient, suggesting that the subsoil is a key region for nitrogen accumulation; the 0–20 cm layer had the lowest coefficient, indicating relatively stable nitrogen content in the topsoil.

3.4.2. Response of nitrogen utilization in rice to nitrogen application rate

Based on model fitting (Fig. 8) and marginal effect analysis (Fig. 9), the integrated critical nitrogen application rate for rice nitrogen utilization was determined to be 199.44 kg/ha, with critical values for agronomic efficiency, nitrogen uptake efficiency, physiological efficiency, and partial productivity at 188.89 kg/ha, 191.11 kg/ha, 197.42 kg/ha, and 210.00 kg/ha, respectively. Marginal effect analysis indicated that the 120–180 kg/ha range exhibited the highest marginal

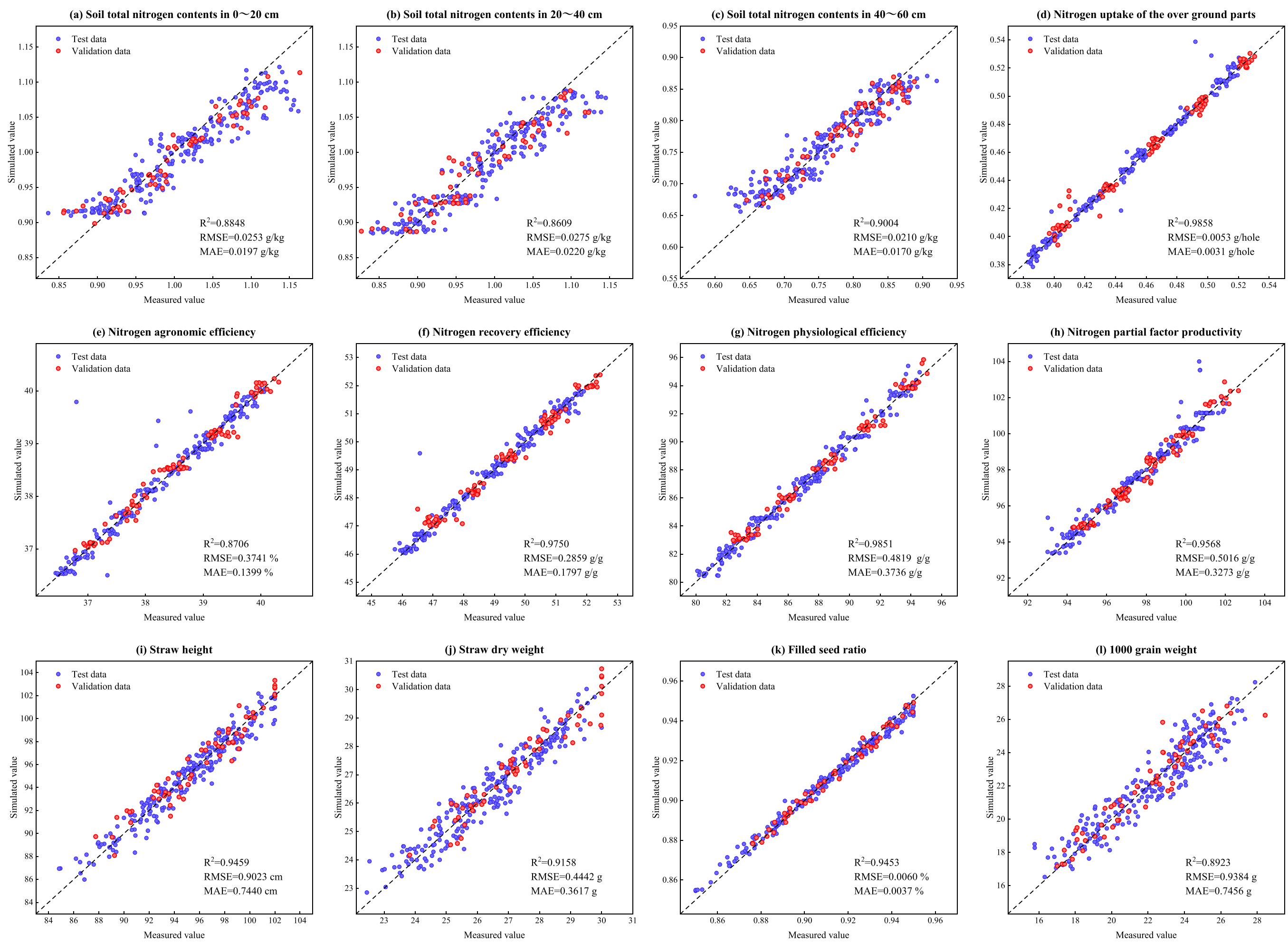

Fig. 6. Comparison between observed and predicted values.

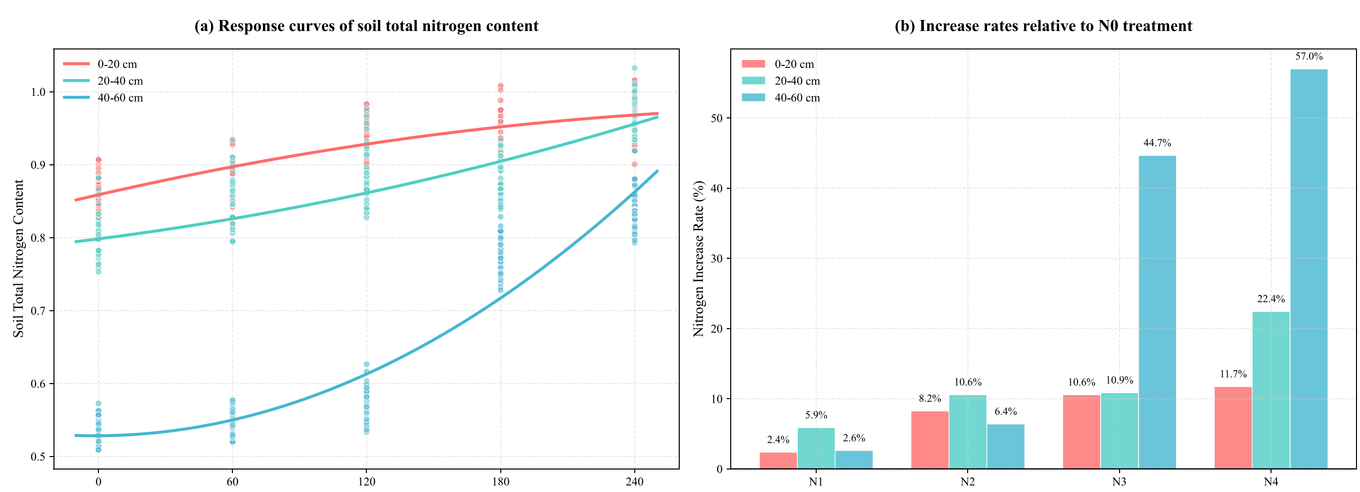

Fig. 7. Response curves of nitrogen application rate and changes in nitrogen increase rate under different treatments.

effects, with marginal values of 0.0376, 0.0299, 0.0649, and 0.0811 units/kg/ha for agronomic efficiency, nitrogen uptake efficiency, physiological efficiency, and partial productivity, respectively, representing the "optimal benefit range" for nitrogen application. In the 180–240 kg/ha range, all indicators exhibited negative marginal effects, with the physiological efficiency showing the steepest decline, indicating that each additional 1 kg/ha of nitrogen in this range reduces utilization efficiency and exerts the most significant negative impact on physiological metabolism.

Under high nitrogen conditions (≥180 kg/ha), rice nitrogen use efficiency exhibited a significant linear decline ($p < 0.05$), further confirming the negative effects of excessive nitrogen application. This pattern is closely associated with increased soil nitrogen leaching, saturation of crop nitrogen uptake, and imbalance in the allocation of

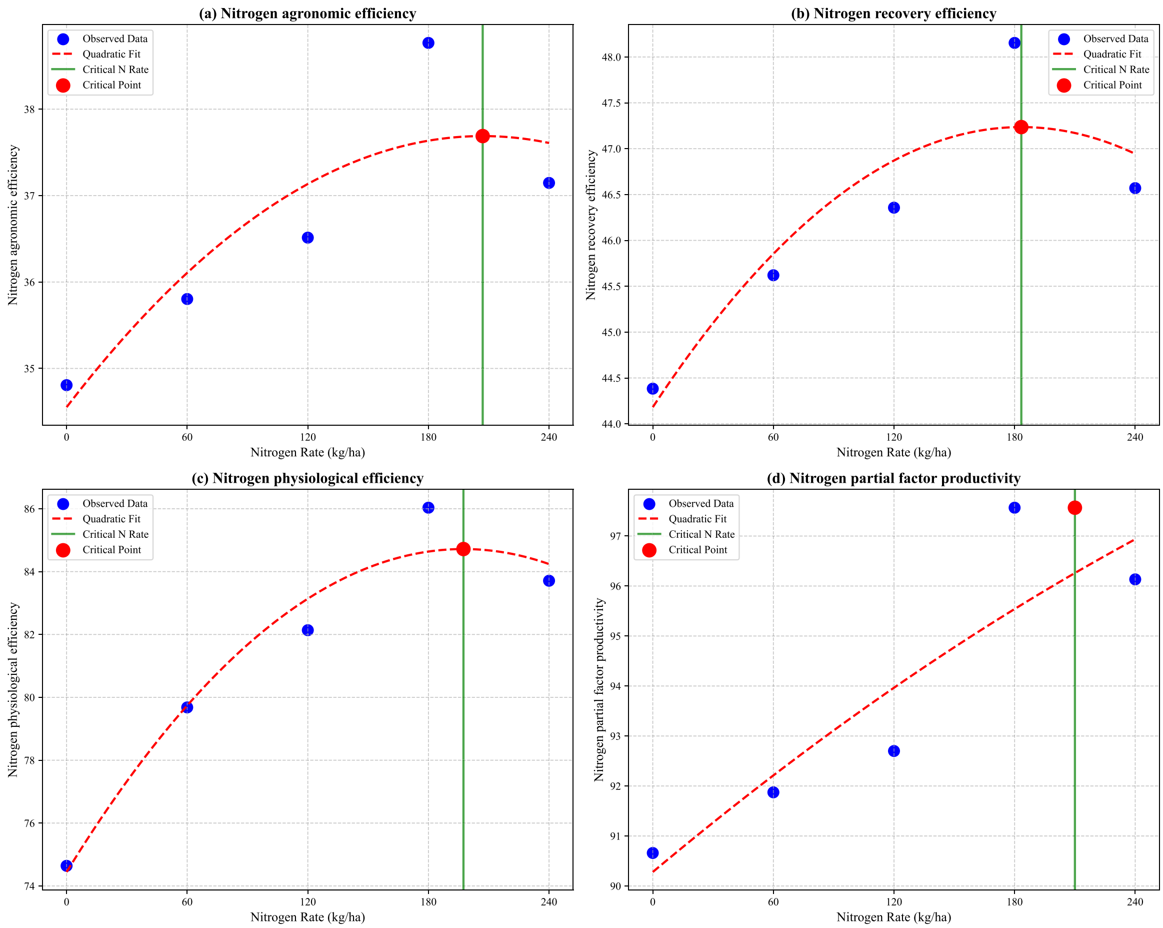

Fig. 8. The critical nitrogen application rate for nitrogen fertilizer utilization in rice.

photosynthetic products; although the mulched drip irrigation system enhances nitrogen use efficiency, it cannot offset the negative effects of excessive nitrogen application.

3.4.3. Response of rice yield components to nitrogen application rate

From the overall distribution of yield component evaluation (Fig. 10), culm height was the most sensitive to nitrogen application, showing a stable linear increase with increasing nitrogen levels. Slope analysis confirmed that the nitrogen response slope of culm height was significantly higher in the high-nitrogen range than in the low-nitrogen range, indicating a markedly accelerated growth rate under high nitrogen, consistent with its physiological role as a core indicator of canopy structure formation, whereby sufficient nitrogen promotes stem cell elongation and photosynthate accumulation, providing a structural basis for canopy light utilization. Stem dry weight accumulation progressively increased with nitrogen application, exhibiting minimal interannual variability. The slope distribution indicates that nitrogen enhances leaf photosynthetic efficiency, promoting allocation of photosynthates to stems, with this effect becoming more pronounced at nitrogen levels above 200 kg/ha. Notably, stem dry weight and culm height were strongly positively correlated (Fig. 11)($r = 0.97$, $p < 0.001$), indicating that nitrogen regulation of rice vegetative growth exhibits "height-dry weight" synergy, jointly determining canopy biomass accumulation. The filled grain ratio is a key link between nitrogen application and other yield components, exhibiting the highest correlation with nitrogen application ($r = 0.88$, $p < 0.001$), and it increases with nitrogen levels. Mediation analysis showed that nitrogen application first increases the filled grain ratio, enhancing the grains' competitive capacity for photosynthates, indirectly promoting the transfer of stem nutrients to grains while maintaining stem structural stability. Thousand-grain weight is a key determinant of final yield and a primary limiting factor for yield improvement, exhibiting a "threshold effect" in response to nitrogen application. The increase in thousand-grain weight with nitrogen application was modest, averaging only 1.0% across three years from N0 to N4 treatments. Threshold analysis further confirmed that thousand-grain weight growth significantly slowed at 55.17 kg/ha nitrogen, with diminishing marginal returns beyond this point. Moreover, thousand-grain weight is most influenced by indirect nitrogen effects, whereby nitrogen first increases the filled grain ratio to optimize grain filling efficiency, then enhances stem dry weight to ensure photosynthate supply, ultimately indirectly promoting thousand-grain weight.

Based on slope and elasticity analyses, the impact of nitrogen application on yield components exhibited a pronounced effect (Fig. 12), allowing the nitrogen application range to be divided into three critical stages, each with distinct regulatory focus and effect characteristics. In the low-nitrogen stage (0–100 kg/ha), the nitrogen response slopes of all components were relatively low, but elasticity coefficients were high, indicating that small increments of nitrogen could significantly activate rice growth potential under low-nitrogen conditions. In the medium-nitrogen stage (100–200 kg/ha), nitrogen response slopes increased significantly, and the growth rates of all components tended to stabilize. At the same time, the model-predicted yield reached 85.71 in 2019 during this stage, approaching the optimal level. Elasticity analysis showed that the average elasticity coefficient of components in the medium-nitrogen stage was 3.25, slightly lower than in the low-nitrogen stage but still high, indicating maximal marginal benefits of nitrogen application in this stage. In the high-nitrogen stage (>200 kg/ha), nitrogen response slopes further increased, but the actual growth of components began to slow, and

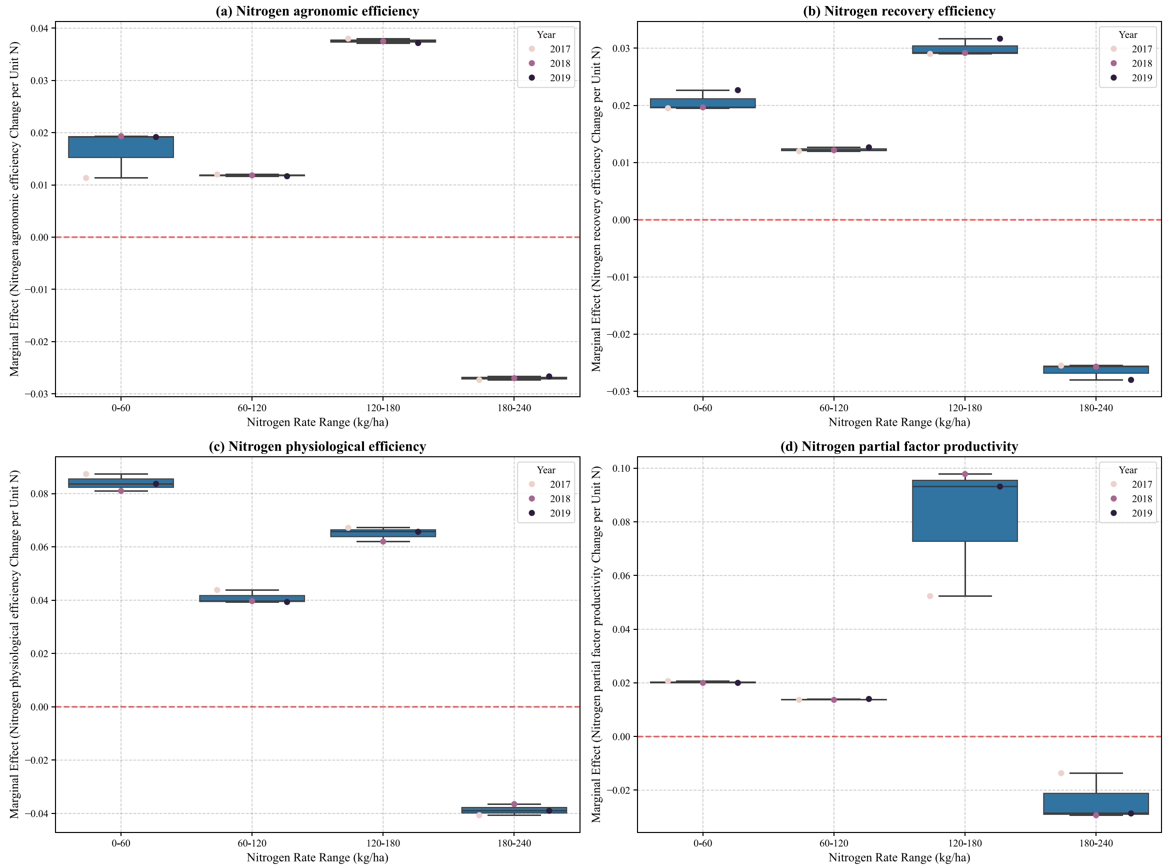

Fig. 9. The marginal influence of nitrogen fertilizer utilization in rice.

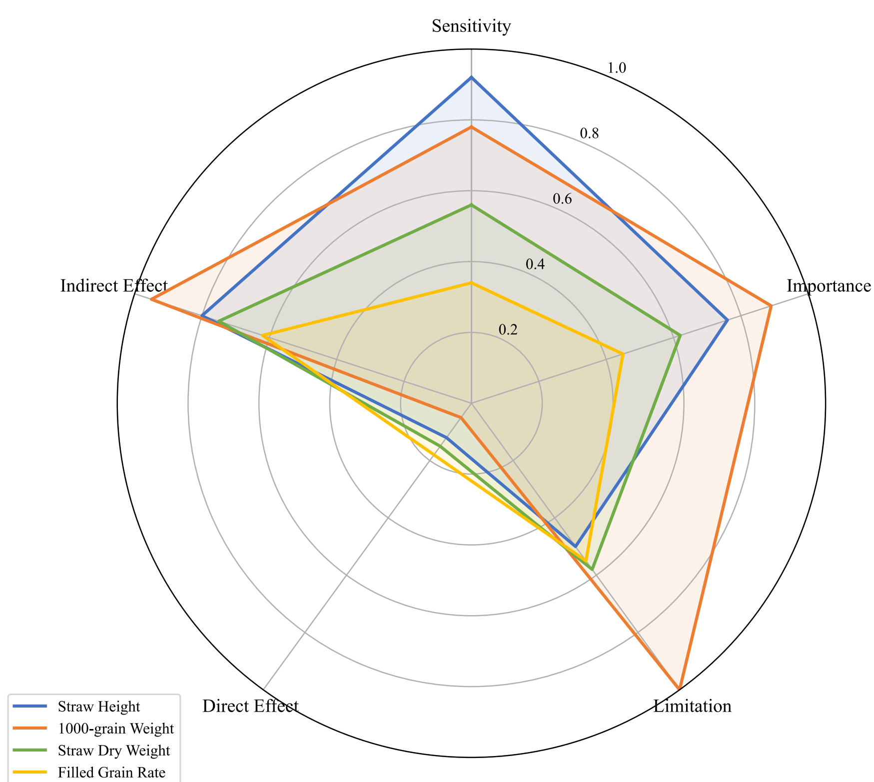

Fig. 10. Comprehensive evaluation of yield components.

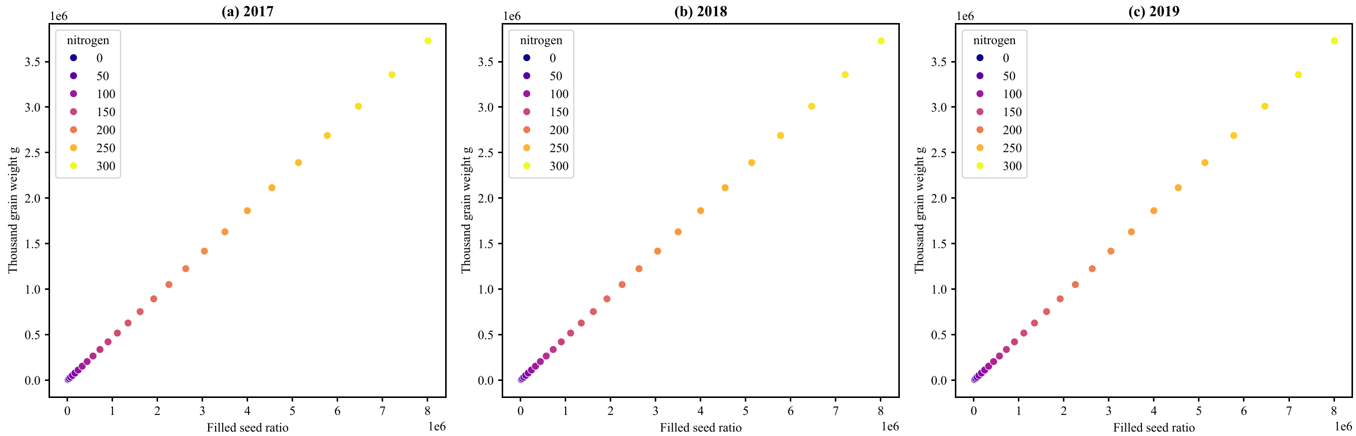

Fig. 11. The relationship between straw height and straw dry weight.

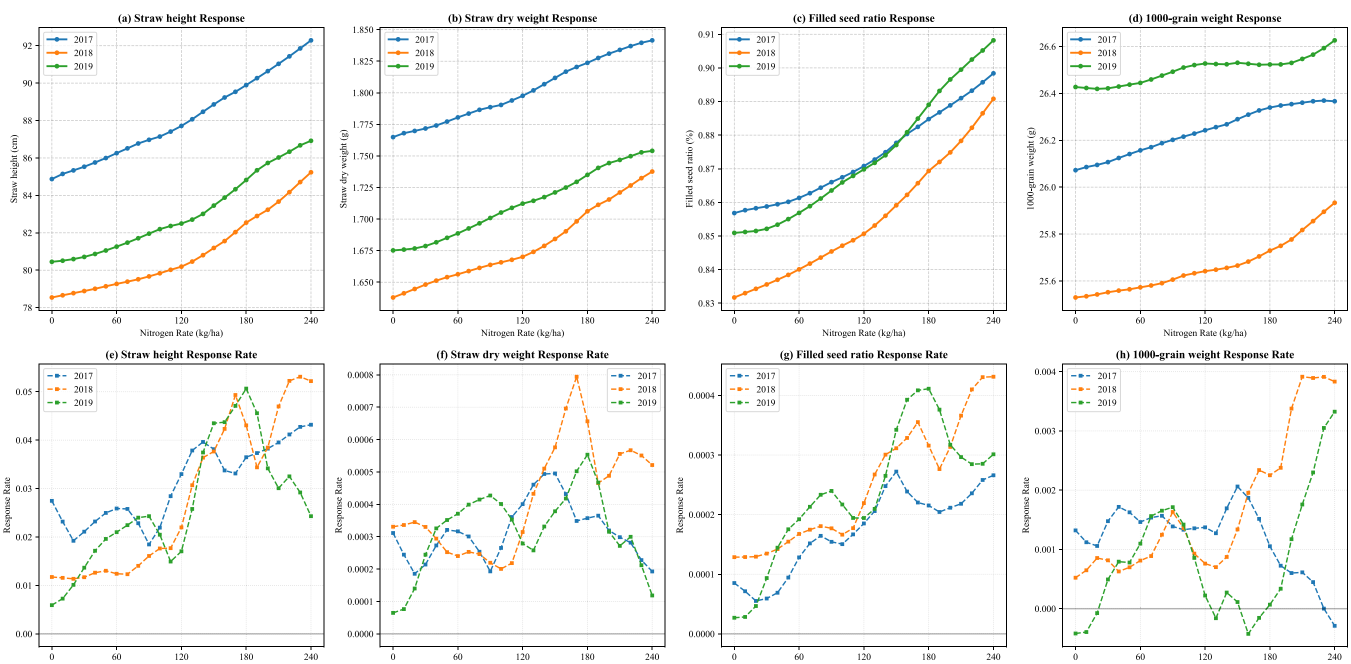

Fig. 12. The influence of N application on yield components.

reproductive growth traits such as thousand-grain weight exhibited "growth stagnation." At the same time, nitrogen use efficiency began to decline in the high-nitrogen stage, indicating that while excessive nitrogen continues to promote vegetative growth, its effect on reproductive growth has reached saturation.

The regulatory effect of nitrogen application on yield components demonstrated strong interannual stability. Data indicated that the trends of all yield components with increasing nitrogen were consistent across years, with no significant interannual reversals. Interannual correlation analysis showed that from 2017 to 2019, under the same nitrogen treatment, the correlation coefficients between culm height and stem dry weight remained above 0.99, indicating that nitrogen regulation of yield components is unaffected by climatic variation and is supported by stable physiological mechanisms.

3.4.4. *Response of rice quality to nitrogen application rate*

Rice quality under mulched drip irrigation is a complex process influenced by multiple interacting factors, where gradient variations in nitrogen application differentially affect key quality traits by regulating plant nitrogen accumulation and carbon-nitrogen metabolic balance. Correlation analysis (Fig. 13) showed that milling quality traits were significantly positively correlated. Among appearance quality traits, chalky rice rate was closely associated with chalkiness, whereas grain length–width ratio was strongly negatively correlated with cooked rice sensory scores. Physicochemical quality traits exhibited varying degrees of correlation both internally and with other quality trait categories.

Different types of rice quality traits exhibited markedly distinct response patterns to nitrogen application. (Fig. 14) Brown rice rate, milled rice rate, gel consistency, and amylose content showed a parabolic trend with increasing nitrogen, initially increasing and then decreasing, indicating a nitrogen response threshold beyond which quality deteriorates due to excessive nitrogen. Chalky rice rate, chalkiness, and protein content continuously increased with nitrogen application, while grain length–width ratio and imperfect grain rate continuously decreased; these quality changes were linearly associated with nitrogen levels, demonstrating a sustained regulatory effect. The head rice rate gradually increased with nitrogen in the early stage and stabilized in the later stage, reflecting a gradual adaptation to nitrogen

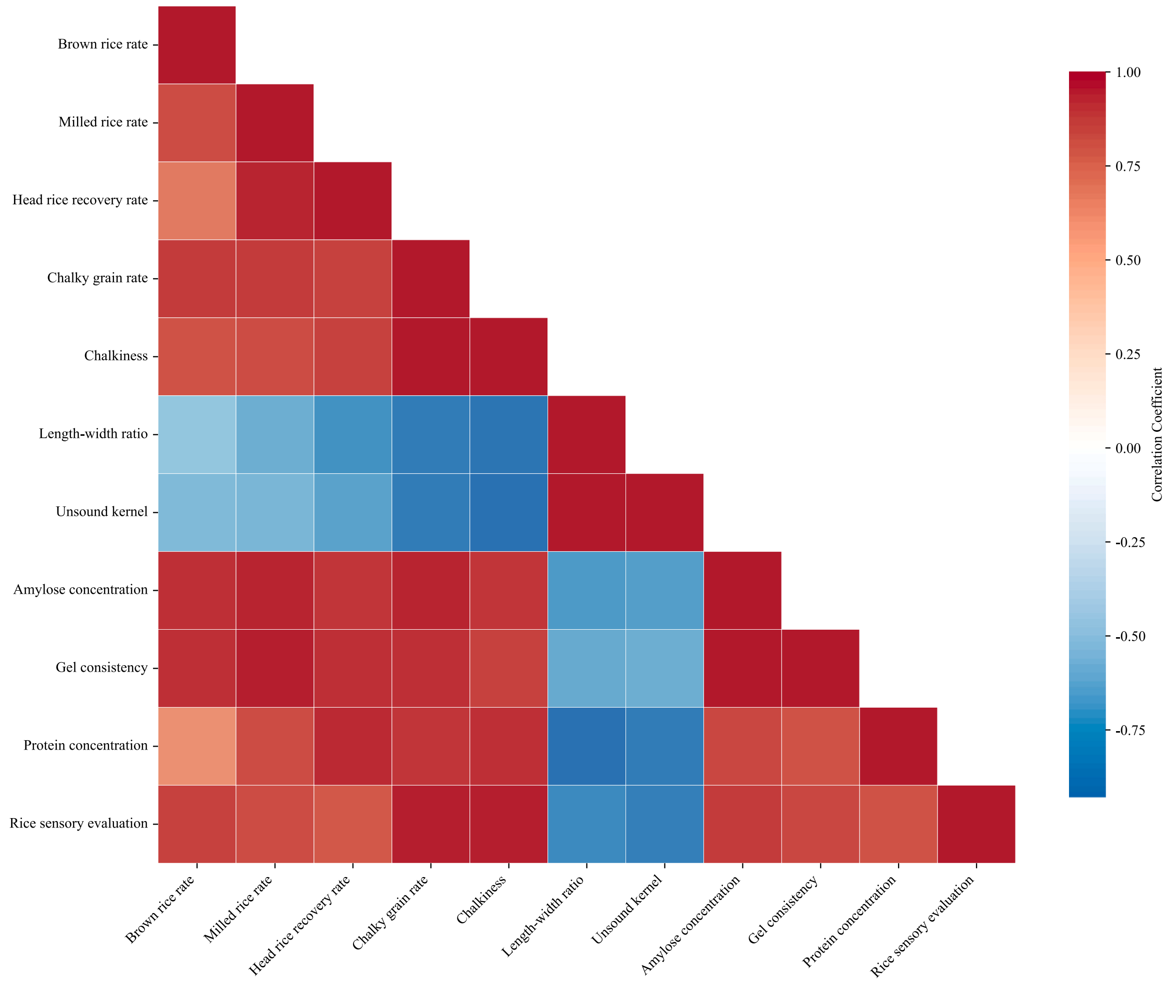

Fig. 13. Correlation analysis among different qualities of rice.

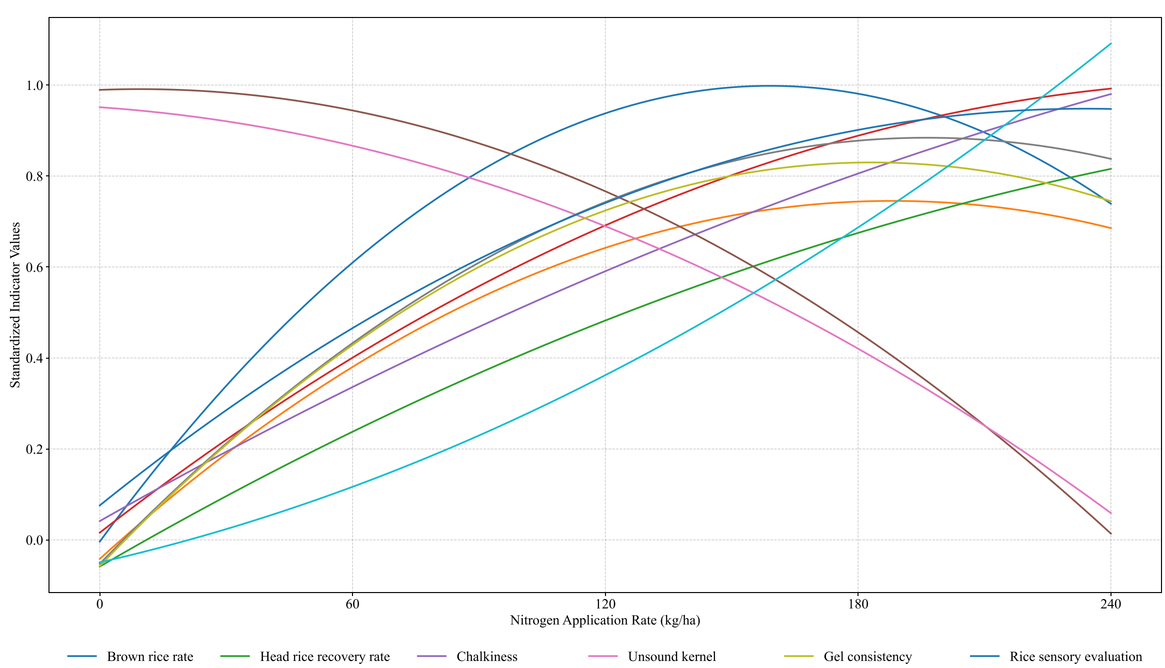

Fig. 14. The responses of different quality indicators to nitrogen application rate.

Table 3
Predictive accuracy and robustness of different models for agronomic response analysis under film-mulched drip irrigation.

Response variable	Model	R^2 (Train)	R^2 (Test)	RMSE (Test)	Cross-validation R^2 (mean±SD)
Soil N	MLR	0.842	0.825	0.032	0.821 ± 0.005
Soil N	DNN	0.896	0.872	0.020	0.868 ± 0.013
NUE	MLR (Baseline)	0.675	0.613	0.315	0.609 ± 0.022
NUE	MLR	0.858	0.776	0.248	0.769 ± 0.025
Yield components	MLR	0.892	0.865	0.112	0.858 ± 0.016
Yield components	CNN	0.885	0.851	0.138	0.845 ± 0.019
Grain quality	MLR	0.888	0.815	0.392	0.807 ± 0.023
Grain quality	Transformer	0.894	0.836	0.360	0.829 ± 0.021

followed by a stable period. Studies indicate that when aiming to optimize both milling and appearance quality, a balance must be sought between the nitrogen threshold and unidirectional trait changes, to prevent the deterioration of other quality traits due to the optimization of a single trait.

There exist latent correlations both within and between different types of rice quality traits. The peak ranges of brown rice rate and milled rice rate highly overlapped with the optimal range of gel consistency, indicating a synergistic regulatory effect of nitrogen on milling and physicochemical quality, allowing simultaneous optimization of both trait categories through nitrogen management. The chalky rice rate and cooked rice sensory score exhibited opposite trends with increasing nitrogen, reflecting a trade-off in nitrogen regulation between appearance and eating quality, necessitating nitrogen management strategies tailored to market preferences.

The effects of nitrogen application on quality traits vary across different nitrogen stages. In the low-nitrogen stage, most traits are in a rapid response phase, where slight changes in nitrogen can cause significant fluctuations in quality. In the medium-nitrogen stage, threshold-type traits enter a peak transition phase, while unidirectional traits experience rapid change. In the high-nitrogen stage, some traits enter a deterioration phase, while others continue to improve. Adjusting nitrogen application during critical growth stages can establish a quality foundation in the low-nitrogen phase, optimize core traits in the medium-nitrogen phase, and avoid quality losses in the high-nitrogen phase, thereby achieving dual improvement in nitrogen use efficiency and rice quality.

3.5. Performance evaluation and robustness analysis

To evaluate the predictive reliability of different deep learning architectures, conventional multiple linear regression (MLR) models were introduced as baseline models for comparison. Model performance was assessed using the coefficient of determination (R^2), root mean square error (RMSE), and repeated k-fold cross-validation analyses.

The results showed that deep learning models consistently outperformed MLR models across different agronomic response tasks (Table 3). For soil nitrogen prediction, the DNN model achieved a higher R^2 and lower RMSE than the corresponding MLR model, indicating stronger capability in capturing multilayer nonlinear relationships within the soil nitrogen profile. Similarly, the MLP model showed improved predictive performance for NUE indicators compared with linear regression approaches, suggesting that nitrogen utilization responses under film-mulched drip irrigation (FMDI) involve complex nonlinear interactions among agronomic variables.

For yield-component analysis, the CNN model exhibited superior performance in characterizing the coupled responses among grain filling, dry matter accumulation, and yield-related traits. In addition, the Transformer model achieved the highest predictive accuracy for grain quality traits, indicating its stronger capability in representing complex dependencies among multiple quality indicators.

Repeated cross-validation analyses further demonstrated relatively stable model performance, with low standard deviations observed for both R^2 and RMSE values across repeated runs (Table 3). These results suggest that the developed deep learning models exhibited acceptable robustness and uncertainty control under the experimental dataset conditions.

Overall, the improved predictive performance of deep learning models over conventional linear approaches indicates that nitrogen regulation under FMDI is governed by complex nonlinear coupling relationships rather than simple linear responses.

4. Discussion

4.1. Soil nitrogen dynamics and NUE responses under FMDI

Nitrogen application significantly affected soil nitrogen distribution and nitrogen use efficiency under film-mulched drip irrigation (FMDI) (Li et al., 2022; Gu et al., 2021). In the present study, soil total nitrogen content increased progressively with increasing nitrogen application rate, particularly in the surface soil layer. This result indicates that nitrogen accumulation under FMDI was closely associated with localized fertigation and concentrated wetting patterns around the root zone. Compared with conventional flooding irrigation, drip irrigation systems generally produce relatively stable wetting fronts and reduced lateral water movement, which may enhance nitrogen retention in the upper soil profile during moderate nitrogen application conditions (Hou et al., 2023).

However, excessive nitrogen input promoted nitrogen migration toward deeper soil layers, indicating a potential increase in nitrogen leaching risk under high fertilization conditions. This phenomenon may be associated with the combined effects of concentrated fertigation, downward water movement, and reduced nitrogen uptake efficiency under excessive nitrogen supply. Under high nitrogen application rates, the nitrogen absorption capacity of rice roots may gradually approach saturation, resulting in increased residual nitrogen in the soil profile and enhanced downward transport driven by soil water movement (Zhou et al., 2021b). Similar findings have been reported in previous studies, which demonstrated that excessive nitrogen application under drip irrigation systems may increase nitrate accumulation in deeper soil layers and reduce overall nitrogen recovery efficiency (Chen et al., 2020).

Nitrogen use efficiency (NUE) exhibited a decreasing trend with increasing nitrogen application rate, suggesting diminishing marginal returns of nitrogen input under FMDI conditions. Moderate nitrogen application improved crop nitrogen uptake and biomass accumulation, thereby enhancing nitrogen productivity. In contrast, excessive nitrogen input may lead to physiological imbalance between vegetative and reproductive growth, reduced nitrogen remobilization efficiency during grain filling, and increased environmental nitrogen losses. These findings indicate that nitrogen management under FMDI should not solely focus on maximizing yield but should simultaneously consider nitrogen utilization efficiency and environmental sustainability.

Compared with many previous studies focusing only on crop productivity, the present study further revealed the coupled responses of soil nitrogen accumulation and NUE decline under excessive nitrogen input (Zhang et al., 2022). This highlights the importance of integrated nitrogen management in water-saving rice cultivation systems.

4.2. Nitrogen regulation of yield formation under FMDI

Nitrogen application significantly influenced rice yield formation under FMDI conditions, and moderate nitrogen input contributed to the coordinated improvement of effective panicle number, grain filling, and grain weight. The results demonstrated that rice yield initially increased and subsequently stabilized or declined with increasing nitrogen application rate, indicating the existence of an optimal nitrogen threshold for yield formation.

Appropriate nitrogen supply can enhance chlorophyll synthesis, canopy photosynthetic capacity, and dry matter accumulation during vegetative growth stages, thereby promoting spikelet differentiation and grain filling. In addition, sufficient nitrogen availability during reproductive stages facilitates assimilate transport from source organs to grains, contributing to improved grain filling percentage and thousand-grain weight. These processes collectively enhance rice productivity under moderate nitrogen conditions.

However, excessive nitrogen application did not continuously improve yield performance. One possible explanation is that excessive nitrogen supply promotes excessive vegetative growth and canopy development, which may increase mutual shading within the canopy and reduce light-use efficiency during later growth stages (Zhou et al., 2021b). In addition, excessive nitrogen may delay plant senescence and disturb the balance between source and sink organs, thereby reducing assimilate remobilization efficiency during grain filling (Zhao et al., 2025). Consequently, the yield increase under high nitrogen conditions became limited despite continued nitrogen input.

The present findings are generally consistent with previous studies reporting that moderate nitrogen application can improve rice yield under water-saving irrigation systems, whereas excessive nitrogen often leads to diminishing yield returns and reduced nitrogen productivity (Liu et al., 2014). Nevertheless, the current study further demonstrated that yield formation under FMDI is closely associated with coordinated regulation among nitrogen availability, canopy growth, and grain filling processes rather than simple linear responses to nitrogen input.

These results suggest that optimizing nitrogen management under FMDI should emphasize balanced crop growth and efficient assimilate allocation instead of pursuing maximum nitrogen input.

4.3. Trade-offs between grain quality and nitrogen application

Nitrogen application exerted significant effects on rice grain quality, but the responses of different quality traits to nitrogen input were not completely consistent. Moderate nitrogen application improved several quality indicators, including milling quality and protein content, whereas excessive nitrogen input negatively affected certain appearance and eating quality traits. These findings indicate that grain quality regulation under FMDI involves complex trade-offs among different quality attributes.

The improvement in protein content under moderate nitrogen conditions may be attributed to enhanced nitrogen assimilation and protein synthesis during grain development (Yoneyama et al., 2016). Nitrogen availability plays an important role in amino acid accumulation and storage protein formation, thereby contributing to improved nutritional quality (Huang et al., 2026). In addition, moderate nitrogen supply may improve grain filling conditions and reduce the proportion of immature grains, which benefits milling quality (Ding et al., 2026).

However, excessive nitrogen application increased chalkiness and reduced eating quality in some treatments. This phenomenon may be associated with altered starch synthesis and disrupted carbonnitrogen balance during grain filling (Chen et al., 2024). Excessive nitrogen often promotes protein accumulation at the expense of starch deposition, which may increase grain opacity and deteriorate texture characteristics (Fan et al., 2022). Furthermore, prolonged vegetative growth under high nitrogen conditions may delay grain maturation and weaken assimilate transport efficiency during late filling stages, thereby negatively affecting grain appearance and eating quality.

These findings suggest that rice quality formation under FMDI is governed by coordinated interactions among nitrogen metabolism, carbon allocation, and grain filling processes. Therefore, optimizing nitrogen management should not solely focus on maximizing individual quality traits but should instead balance multiple quality indicators together with yield and nitrogen use efficiency.

Compared with previous studies emphasizing single quality parameters, the present study further highlighted the nonlinear and trait-specific responses of grain quality to nitrogen application under FMDI conditions. This also explains why the optimal nitrogen rate should be determined based on integrated evaluation rather than isolated quality indicators.

4.4. Nonlinear response characteristics and nitrogen threshold identification

The deep learning models employed in this study demonstrated strong capability in characterizing nonlinear response relationships among nitrogen application, soil nitrogen dynamics, NUE, yield formation, and grain quality under FMDI conditions. Compared with conventional regression approaches, deep learning models can better capture complex interactions and coupled responses among multiple agronomic variables, thereby improving the representation of nonlinear nitrogen response characteristics (De Clercq and Mahdi, 2025; Kamilaris and Prenafeta-Boldú, 2018).

The results indicated that rice growth and quality traits exhibited evident threshold responses to nitrogen input. Moderate nitrogen application promoted coordinated improvement in soil nitrogen availability, nitrogen utilization, yield formation, and grain quality, whereas excessive nitrogen input resulted in reduced NUE, increased nitrogen accumulation in deeper soil layers, and deterioration of some quality traits. These findings suggest that the responses of rice systems to nitrogen input are characterized by nonlinear regulation rather than continuous positive feedback.

Among the tested nitrogen treatments, the moderate nitrogen application level achieved relatively balanced performance in yield, grain quality, and NUE, indicating that excessive nitrogen input may not provide proportional agronomic benefits under FMDI conditions. This result further highlights the importance of threshold-based nitrogen management strategies for sustainable rice production in arid irrigation regions.

Although deep learning models provided improved capability for nonlinear response characterization, several limitations should also be acknowledged. The current study was conducted under specific climatic and soil conditions in Ningxia, China, and the applicability of the identified nitrogen threshold to other ecological regions requires further validation. In addition, although deep learning models effectively captured complex response patterns, the interpretation of agronomic mechanisms still relied primarily on statistical relationships rather than direct physiological evidence. Future studies should integrate root-zone monitoring, nitrogen transport measurements, and explainable artificial intelligence methods to further improve mechanistic understanding of nitrogen regulation under FMDI systems (Ahmed et al., 2025).

4.5. Study limitations and future perspectives

Although this study systematically evaluated the effects of nitrogen application on soil nitrogen dynamics, nitrogen use efficiency, yield formation, and grain quality under film-mulched drip irrigation (FMDI), several limitations should be acknowledged.

The field experiment was conducted in Ningxia, China, under arid climatic conditions and specific soil characteristics. Therefore, the identified nitrogen response thresholds and agronomic relationships may be influenced by local environmental conditions, including climate, soil texture, irrigation regime, and rice cultivar. The applicability of the present findings to other ecological regions or cultivation systems requires further validation through multi-site experiments.

Although the three-year field experiment improved the reliability of the dataset, the temporal scale of this study was still relatively limited for evaluating long-term soil nitrogen accumulation and environmental effects under continuous FMDI management. Long-term monitoring is needed to further assess the sustainability of nitrogen management strategies and their potential impacts on soil fertility and nitrogen leaching risk.

The present study mainly focused on aboveground agronomic responses and soil nitrogen distribution, whereas direct measurements of root growth dynamics, rhizosphere nitrogen transformation, and subsurface nitrate transport were not included. Consequently, the interpretation of nitrogen migration and utilization processes still relied partly on indirect statistical relationships rather than direct physiological evidence.

In addition, although deep learning models demonstrated strong capability in characterizing nonlinear response relationships, the current analysis primarily emphasized predictive and response-pattern interpretation. The interpretability of deep learning models in agricultural systems remains limited compared with process-based physiological models. Future studies should further integrate explainable artificial intelligence approaches, root-zone monitoring, and process based modeling frameworks to improve mechanistic understanding of nitrogen regulation under FMDI conditions.

Despite these limitations, the present study provides an integrated analytical framework for evaluating the coupled responses of soil nitrogen dynamics, nitrogen utilization, yield formation, and grain quality under different nitrogen application conditions. The findings contribute to the development of precision nitrogen management strategies for sustainable rice production in arid irrigation regions.

5. Conclusions

This study systematically evaluated the coupled responses of soil nitrogen dynamics, nitrogen use efficiency (NUE), yield formation, and grain quality to different nitrogen application rates under film-mulched drip irrigation (FMDI) in the arid irrigation region of Ningxia, China. The results demonstrated that nitrogen regulation under FMDI exhibited evident nonlinear threshold characteristics under the local climatic and soil conditions characterized by low precipitation, high evaporation, and saline-alkaline alluvial soils. Moderate nitrogen application promoted coordinated improvement in nitrogen uptake, dry matter accumulation, grain filling, and grain quality, whereas excessive nitrogen input increased nitrogen accumulation in deeper soil layers, reduced NUE, and negatively affected certain quality traits. These findings indicate that rice responses to nitrogen input under FMDI are governed not by continuous positive feedback but by complex trade-offs among soil nitrogen retention, crop growth, assimilate allocation, and grain quality formation. Deep learning models further revealed the nonlinear coupling relationships among nitrogen application, agronomic traits, and quality responses, highlighting the importance of threshold-based nitrogen management for sustainable rice production in arid irrigation systems. Comprehensive evaluation suggested that 180 kg ha^{-1} was the optimal nitrogen application rate for balancing productivity, grain quality, and nitrogen utilization under the experimental conditions of this study. However, the identified nitrogen threshold and response relationships may vary under different climatic conditions, soil textures, irrigation regimes, and rice cultivars. Therefore, further multiregional and long-term studies integrating root-zone processes, nitrogen transport monitoring, and explainable artificial intelligence approaches are still needed to improve mechanistic understanding and broader regional applicability of nitrogen management strategies under FMDI systems.

CRediT authorship contribution statement

Hailin Yang: Formal analysis, Data curation. **Dengyu Zhang:** Formal analysis, Data curation. **Xinxin Li:** Formal analysis, Data curation. **Qingqing Yang:** Formal analysis, Data curation. **Xinyu Wen:** Formal analysis, Data curation. **Xianyuan Bao:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Jinyu He:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Sikai Li:** Writing – original draft, Resources, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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