

## Effects of Irrigation Methods and Optimized Nitrogen Application Patterns with Straw Mulching on Straw Decomposition Characteristics and Rice Nitrogen Utilization (Postprint)

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### Abstract

Using hybrid indica rice ‘F You 498’ as experimental material, this study investigated the effects of different irrigation methods [flooding irrigation (CK), alternate wetting and drying irrigation, dryland farming] and optimized nitrogen management models with straw mulching (wheat straw mulching optimized nitrogen application model, rapeseed straw mulching optimized nitrogen application model, and no straw mulching optimized nitrogen application model) on rice root growth, nitrogen accumulation at various growth stages, and grain yield, explored the decomposition and nitrogen release patterns of straw under different irrigation methods, and clarified the effects of straw decomposition and nitrogen release patterns on rice growth and their correlations. The results showed that both flooding irrigation and alternate wetting and drying irrigation effectively coordinated above-ground and below-ground growth of rice at various stages compared with dryland farming, promoted nitrogen absorption and utilization at various stages, and increased grain yield; whereas water use efficiency was highest under dryland farming, followed by alternate wetting and drying irrigation, but the difference was not significant. The peak decomposition and nitrogen release efficiency of both wheat straw and rapeseed straw occurred at 30 days after transplanting, but the decomposition amount and nitrogen release quantity were affected by irrigation method and straw type; rapeseed straw decomposition amount was significantly higher than that of wheat straw, and dryland farming was significantly higher than alternate wetting and drying and flooding irrigation; while nitrogen release amount was optimal with wheat straw. Straw mulching optimized management models also had significant effects on various rice growth indices; under flooding and alternate wetting and drying irrigation, the wheat straw mulching optimized

nitrogen management model effectively coordinated rice plant growth at various stages, promoted nitrogen absorption and utilization, and ultimately achieved yield increases; the rapeseed straw mulching optimized nitrogen management model showed slight inhibitory effects on rice growth throughout the entire growth period; whereas under dryland farming, both wheat straw and rapeseed straw optimized nitrogen application mulching models showed significant promoting effects, with rapeseed straw mulching having a clear advantage, which can serve as a reference for production under water-deficient conditions. Correlation analysis between straw decomposition amount, nitrogen release amount and rice root dry weight, nitrogen absorption and utilization, and yield showed that straw decomposition amount at 30 days after transplanting showed significant negative correlations with grain yield and nitrogen absorption ( $r = 0.27^*_{0.29}$ ), while nitrogen release amount at full heading stage and maturity stage showed significant positive correlations with simultaneously, straw decomposition amount and nitrogen release had substantial effects on rice root-shoot ratio, with the most significant effects at full heading stage ( $r = 0.27^* \sim 0.42^{**}$ ). Coordinating straw decomposition amount and nitrogen release at various rice growth stages, particularly nitrogen release amount at 30 days after transplanting, is one of the important measures to ensure high yield and high efficiency in rice production.

## Full Text

### Preamble

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### **Effects of irrigation method and straw mulch-nitrogen management pattern on straw decomposition characteristics and nitrogen utilization of hybrid rice\***

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### Abstract

Irrigation methods have both direct effect and remote effect (through straw decomposition and nitrogen release especially when integrated with nitrogen management) on rice growth. A field experiment was conducted to evaluate the effect of irrigation methods and optimal straw mulch-nitrogen management pattern on root growth, nitrogen accumulation at main growth stages and grain yield of hybrid rice. Also straw decomposition and nitrogen release mechanisms

were probed to clarify the effects of the interaction of straw decomposition and nitrogen release on rice growth. The results showed that flooding irrigation (W0) and alternate wetting and drying irrigation (W1) methods generally coordinated aboveground growth with underground growth, promoted nitrogen accumulation and increased grain yield compared with drought farming (W2). However, the water productivity in W2 treatment was the highest among all treatments, followed by W1. For wheat and rape straw decomposition and nitrogen release, the peak values occurred 30 days after transplanting (30 DAT). However, the degree of decomposition and nitrogen release were influenced by both irrigation methods and straw types. The rape straw under W2 treatment had larger degree of decomposition, while wheat straw under W1 led to more nitrogen release. For straw mulch-nitrogen management patterns, wheat straw combined with optimal nitrogen management (S1N1) under W0 and W1 treatments efficiently coordinated the growth, promoted nitrogen absorption and eventually increased grain yield. However, rape straw combined with optimal nitrogen management (S2N1) had a slight inhibitory effect on the whole growth. Under drought irrigation, S1N1 and S2N1 had positive and remarkable effects on growth. Correlation coefficients showed that the effect of the degree of straw decomposition on the 30DAT was significantly negatively correlated with yield and nitrogen accumulation ( $r = 0.27^*$  to  $0.29$ ). *Also the effect of the degree of nitrogen release at heading and ripening stages was strongly positively correlated with yield and nitrogen absorption ( $r = 0.31$  to  $0.59$ ).* **Also the effects of the degrees of straw decomposition and nitrogen release on root and shoot growth was strong, especially for the heading stage ( $r = 0.27^*$  to  $0.42$ ).** The results suggested that it was important for high grain yield and high efficiency of rice production to coordinate the straw decomposition and nitrogen release at different growth stages of rice, especially at 30 days after transplanting.

### Keywords

Rice; Straw mulch; Nitrogen management; Irrigation method; Straw decomposition; Straw nitrogen release; Nitrogen utilization

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## Introduction

Rice (*Oryza sativa*) is a major food crop in China, and ensuring increased rice production is crucial for national food security. In recent years, rice yields in China have shown an annual increasing trend, but this has been accompanied by

a sharp increase in water and fertilizer use, particularly water and nitrogen, and a rapid decline in water and nitrogen use efficiency, further exacerbating water resource shortages and rice production costs[1]. Meanwhile, most rice-growing regions in southern China practice double or multiple cropping systems. Therefore, during the transition between rice cropping seasons, how to efficiently and quickly manage straw from previous crops[2 4], ensure timely farming, reduce environmental pollution and resource waste, and achieve efficient and sustainable utilization of straw, water, and nitrogen has become increasingly urgent. Previous studies have extensively investigated the theory and technology of straw return combined with water and nitrogen management[5 7]. Results showed that under different water and nitrogen application conditions, straw return could effectively promote rice uptake and utilization of nitrogen, phosphorus, and potassium, increase grain yield and water use efficiency, and improve soil physical and chemical properties in paddy fields. However, there remain some disagreements regarding the effects of specific optimized combinations of straw return with water and nitrogen management on rice growth and nitrogen uptake at different growth stages. Furthermore, the effects of water and nitrogen management on straw decomposition and nitrogen release patterns during the straw mulching process require further investigation. The interactive relationship between straw decomposition and nitrogen release patterns and rice growth has rarely been reported. Therefore, based on previous studies[8 9], this research investigated optimized straw mulching-nitrogen management patterns under different irrigation methods to examine their effects on rice nitrogen uptake and utilization, yield, and straw decomposition and nitrogen release patterns, as well as their relationships. The objectives were to further enrich and supplement the water-fertilizer regulation mechanisms of straw return and nitrogen management, achieve water conservation, fertilizer reduction, high yield, and high efficiency, and provide a theoretical basis and practical guidance for straw return technology systems in rapeseed (*Brassica campestris*)-rice and wheat (*Triticum aestivum*)-rice double-cropping regions.

## 1.1 Experimental Design

The field experiment was conducted in 2014 at the experimental farm of the Rice Research Institute of Sichuan Agricultural University in Wenjiang, Chengdu. Rice seeds were sown on April 10 and raised in dry nursery beds. Seedlings were transplanted on May 18 using a high-yield cultivation method of wide-narrow row spacing (40 cm wide rows, 26.7 cm narrow rows, and 16.7 cm plant spacing) proposed in previous studies[8 9]. Single seedlings were planted per hill, and different crop straw mulching treatments were applied in the wide rows to facilitate straw return operations. The experimental field had sandy loam soil in the plow layer, containing organic matter  $20.08 \text{ g} \cdot \text{kg}^{-1}$ , total nitrogen  $1.26 \text{ g} \cdot \text{kg}^{-1}$ , alkaline hydrolysis nitrogen  $95.44 \text{ mg} \cdot \text{kg}^{-1}$ , available phosphorus  $33.32 \text{ mg} \cdot \text{kg}^{-1}$ , available potassium  $88.46 \text{ mg} \cdot \text{kg}^{-1}$ , and pH 6.40. Pre-return straw nitrogen content was  $7.47 \text{ g} \cdot \text{kg}^{-1}$  for wheat straw and  $5.33 \text{ g} \cdot \text{kg}^{-1}$  for rapeseed straw. Total rainfall during the rice season was  $7,848 \text{ m}^3 \cdot \text{hm}^{-2}$ .

A two-factor split-plot design was employed, with irrigation method as the main plot and optimized straw mulch-nitrogen combinations from previous studies as the sub-plot. Three irrigation methods were established in the main plots: flooding irrigation (control, W0), where a 1–3 cm water layer was maintained after transplanting until natural drying one week before harvest; controlled alternate wetting and drying irrigation (W1), where shallow water (approximately 1 cm) was maintained at transplanting, a 2 cm water layer was kept for 5–7 days after transplanting to ensure seedling survival, fields were dried during the ineffective tillering stage, and subsequent growth stages employed alternate irrigation by applying shallow water (approximately 2 cm) and re-irrigating when soil cracks appeared; and dry farming (W2), where soil was thoroughly watered before transplanting, followed by dryland management throughout the growth period (relying entirely on natural rainfall). All plots were irrigated using water pumps to precisely extract water from irrigation channels, and water meters accurately recorded the amount applied to each plot. All plots were allowed to dry naturally during the growth period without drainage. The sub-plots consisted of optimized nitrogen management with wheat straw mulching, rapeseed straw mulching, and no straw mulching, designated as S1N1, S2N1, and S0N1, respectively. Both crop straws were returned to the field at full amounts from external sources ( $5,000 \text{ kg} \cdot \text{hm}^{-2}$  wheat straw and  $7,000 \text{ kg} \cdot \text{hm}^{-2}$  rapeseed straw). After harvest, rapeseed and wheat straws were cut into 5–10 cm pieces and uniformly mulched in the wide rows after rice transplanting. Details of the experimental design are shown in Table 1.

The nitrogen application rate (urea, 46% N) was  $135 \text{ kg} \cdot \text{hm}^{-2}$ , applied in a basal fertilizer:tillering fertilizer:panicle fertilizer ratio of 3:3:4. The tillering fertilizer was applied 7 days after transplanting, and the panicle fertilizer was applied once at the 4th leaf stage from the top (specific combinations are shown in Table 1). Phosphorus fertilizer (calcium superphosphate) was applied at  $90 \text{ kg} \cdot \text{hm}^{-2}$  P O, and potassium fertilizer (potassium chloride) at  $150 \text{ kg} \cdot \text{hm}^{-2}$  K O, both applied entirely as basal fertilizer. The experiment had three replications, with each plot area of  $15.6 \text{ m}^2$ . Ridges (40 cm wide) were built between plots and wrapped with plastic film to prevent water and fertilizer leakage. Meteorological data including precipitation, distribution, and average temperature during the 2014 rice growing season (April–early September) were provided by the Sichuan Meteorological Bureau (Figure 1 [Figure 1: see original paper]).

### 1.2.1 Straw Decomposition and Nitrogen Release

Before straw return, a certain amount of wheat and rapeseed straw was cut into 5–10 cm pieces, placed in 40-mesh nylon mesh bags, and mulched in the wide rows of each plot before transplanting. At pre-transplanting, 20 and 30 days after transplanting (DAT), heading, and maturity stages, three bags were randomly selected from each plot, washed clean with water, killed at  $105 \text{ }^\circ\text{C}$  for 30 minutes, dried to constant weight at  $80 \text{ }^\circ\text{C}$ , ground into powder after drying and weighing (passed through an 80-mesh sieve), digested with concentrated

H<sub>2</sub>SO<sub>4</sub> and Kjeldahl catalyst, and analyzed for nitrogen content using a FOSS-8400 Kjeldahl nitrogen analyzer.

### 1.2.2 Rice Nitrogen Accumulation

At 20 and 30 days after transplanting (DAT), heading, and maturity stages, three representative rice plants were sampled from each plot according to the average tiller number, and separated into roots, stems, leaves, and panicles (at heading and maturity). Samples were killed at 105 °C for 30 minutes, dried to constant weight at 80 °C. The dried stems, leaves, and panicles were ground into powder (passed through an 80-mesh sieve), digested with concentrated H<sub>2</sub>SO<sub>4</sub> and Kjeldahl catalyst, and analyzed for nitrogen content using a FOSS-8400 Kjeldahl nitrogen analyzer.

### 1.2.3 Rice Root Dry Weight

At 20 and 30 days after transplanting (DAT), heading, and maturity stages, three representative rice plants were sampled from each plot according to the average tiller number. Root samples were collected as soil columns centered on the plant (26.7 cm × 16.7 cm area, 30 cm depth), placed in 40-mesh nylon mesh bags, washed with running water to obtain intact root systems, killed at 105 °C for 30 minutes, and dried to constant weight at 80 °C.

## 1.3 Parameter Calculations

$$\text{氮肥回收利用率} = \frac{\text{施氮区植株总吸氮量} - \text{无氮区植株总吸氮量}}{\text{施氮量}} \times 100\% \quad (1)$$

$$\text{氮肥农学利用率} = \frac{\text{施氮区稻谷产量} - \text{无氮区稻谷产量}}{\text{施氮量}} \times 100\% \quad (2)$$

$$\text{氮肥生理利用率} = \frac{\text{施氮区产量} - \text{无氮区产量}}{\text{施氮区植株总吸氮量} - \text{无氮区植株总吸氮量}} \times 100\% \quad (3)$$

$$\text{结实期茎秆干物质贡献率} = \frac{\text{齐穗期茎秆干重} - \text{成熟期茎秆干重}}{\text{成熟期穗干重}} \times 100\% \quad (4)$$

$$\text{秸秆腐熟量} = \text{前一时期干重} - \text{该时期干重} \quad (5)$$

$$\text{秸秆氮素释放量} = \text{前一时期氮素含量} - \text{该时期氮素含量} \quad (6)$$

## 1.4 Data Analysis

Experimental data were analyzed using Microsoft Excel 2007, DPS 6.5, and SPSS 17.0 software.

## 2.1 Effects of Irrigation Method and Straw Mulch-Nitrogen Management Pattern on Straw Decomposition and Nitrogen Release

As shown in Table 2, irrigation methods and straw mulch-nitrogen management patterns had significant or highly significant effects on straw decomposition and nitrogen release, with significant interaction effects. Comparing different irrigation methods, during 20–30 days after transplanting (DAT), the decomposition amount and rate of wheat and rapeseed straw under W0 and W1 were lower than under W2. During the period from 30 DAT to heading, there were no significant differences in straw decomposition between W0 and W2, but W1 showed significantly lower decomposition. For nitrogen release amount and rate, W2 showed significant increases compared with W0 at all growth stages, while compared with W1, W2 showed improvement only at 30 DAT with no significant differences at other stages. Under different optimized nitrogen management patterns, compared with N0, N1 significantly increased decomposition of wheat and rapeseed straw during 20–30 DAT and from heading to maturity, but decreased decomposition during 30 DAT to heading. For nitrogen release, N0 showed higher release than N1 only during 20–30 DAT, while N0 was lowest at all other stages. The total straw decomposition amount was highest for rapeseed straw combined with N1, whereas nitrogen release amount was significantly enhanced under wheat straw mulching combined with N1.

## 2.2 Effects of Irrigation Method and Straw Mulch-Nitrogen Management Pattern on Rice Root Growth

As shown in Table 3, irrigation methods and straw mulch-nitrogen management patterns had significant or highly significant effects on root dry weight and root-shoot ratio at various rice growth stages, with significant or highly significant interaction effects. Comparing different irrigation methods, W0 showed significant increases over other irrigation methods at all stages except for a significant decrease in root-shoot ratio at maturity compared with W2, while W1 showed a significant increase in root-shoot ratio only at 20 DAT compared with W2, but decreases compared with W0 and W2 at other stages. Regarding different straw mulch-nitrogen optimization treatments, under W0 and W1, S1N1 significantly increased root dry weight at all growth stages compared with corresponding irrigation methods, while showing a decreasing trend in root-shoot ratio. S0N1 and S2N1 showed no significant differences in root dry weight during early and middle growth stages, but S2N1 achieved the highest root dry weight at maturity. Under W2, straw mulching treatments showed consistent trends in root dry weight and root-shoot ratio with W1 and W2 treatments during early growth stages, but during later stages, S2N1 treatment significantly increased root dry weight compared with other treatments.

### 2.3 Effects of Irrigation Method and Straw Mulch-Nitrogen Management Pattern on Rice Nitrogen Uptake and Utilization

As shown in Table 4, under different irrigation methods, W1 significantly increased nitrogen accumulation during early and late growth stages, total nitrogen, and nitrogen recovery efficiency compared with W0, but decreased nitrogen accumulation during middle growth stage, nitrogen physiological efficiency, and nitrogen agronomic efficiency. W2 showed improvements only in nitrogen accumulation and physiological efficiency during middle growth stage, with significant reductions in all other aspects compared with W0. From the perspective of different straw mulch and nitrogen optimization patterns, straw mulching had highly significant effects on nitrogen accumulation and utilization at all growth stages. Under the same irrigation method, nitrogen uptake at all stages was significantly lower in treatments without nitrogen application. Compared with S0N1, S1N1 under W0 showed significant decreases during early and late growth stages but significantly higher nitrogen accumulation during middle growth stage; W1 showed opposite trends. Under W2, S1N1 significantly increased nitrogen accumulation at all growth stages compared with S0N1. Compared with S0N1, S2N1 significantly increased nitrogen accumulation during early and middle growth stages under W0, W1 without nitrogen, and W2 with nitrogen, but decreased accumulation during late growth stage; other treatments showed decreases only during early growth stage with increases at other stages. Regarding nitrogen use efficiency, compared with S0N1, S1N1 and S2N1 under W1 showed improved nitrogen recovery efficiency but reduced other efficiency metrics, particularly significant for S2N1. Under W2, S1N1 and S2N1 showed improvements in nitrogen recovery and agronomic efficiencies but a decreasing trend in physiological efficiency. Under W1, S1N1 and S2N1 treatments showed reduced efficiency except for improved nitrogen recovery efficiency in S1N1. Overall, W1S1N1 demonstrated clear advantages in total nitrogen uptake and utilization.

### 2.4 Correlation Analysis

Correlation analysis of the effects of straw decomposition amount and nitrogen release on nitrogen uptake and total nitrogen accumulation at various stages, nitrogen use efficiency, and aboveground and belowground rice growth (Table 5) showed that, regarding straw decomposition amount, there were no significant correlations with grain yield, nitrogen accumulation, or nitrogen physiological efficiency at any stage, but significant or notable correlations existed with nitrogen recovery efficiency and root-shoot ratio at various stages. Nitrogen recovery efficiency was significantly negatively correlated with straw decomposition at heading and maturity stages ( $r = -0.31^*$  and  $-0.32$ ). *Meanwhile, straw decomposition at these stages showed no significant correlation with root-shoot ratio, but had significant correlations with the previous or subsequent stages ( $r = -0.28$  and  $-0.32$ ). Regarding nitrogen release amount, straw nitrogen release at 20 and*

30 DAT showed significant or highly significant positive correlations with root-shoot ratio at various stages ( $r = 0.27$  to  $0.50$ ), but negative correlations with total nitrogen accumulation, yield, nitrogen accumulation before heading stage, and nitrogen physiological efficiency. Specifically, nitrogen release at 30 DAT was significantly negatively correlated with yield, total nitrogen accumulation, and nitrogen accumulation during 20-30 DAT ( $r = -0.27$ ,  $-0.29$ , and  $-0.28$ ). In contrast, nitrogen release at heading and maturity stages showed significant or highly significant positive correlations with yield, total nitrogen accumulation, and nitrogen uptake and utilization efficiency ( $r = 0.30^*$  to  $0.59^*$ ), but no significant correlation with root-shoot ratio at corresponding stages.

### 3.1 Effects of Irrigation Method and Straw Mulch-Nitrogen Management Pattern on Straw Decomposition and Nitrogen Release Rate

The rate and amount of straw decomposition and nutrient element release are influenced by irrigation method, cultivation pattern, soil, and climatic environmental factors[10]. Li et al.[11] studied decomposition and nutrient release patterns under wheat and rapeseed straw mulching, finding that both straw types exhibited a pattern of rapid early decomposition followed by slower later decomposition, but wheat straw decomposed slower than rapeseed straw in the early stage while decomposing significantly more in the later stage; their study also indicated relatively slow nitrogen release. Wu et al.[12] investigated the effects of different rice cultivation patterns and straw return methods on decomposition characteristics and nutrient release patterns of wheat and rapeseed straw, reporting that flooding and alternate wetting and drying irrigation created different decomposition patterns, though the difference in straw decomposition rates between the two cultivation patterns was not significant. The effects of cultivation pattern and straw return method on carbon, nitrogen, and phosphorus release rates were generally consistent with their effects on straw decomposition rates, and rapeseed straw showed higher final decomposition and nitrogen release amounts than wheat straw overall. This study demonstrated that under all irrigation methods, the peak decomposition and nitrogen release efficiency of wheat and rapeseed straw occurred in the early stage after straw return, peaking around 30 days after rice transplanting. However, straw decomposition amount and nitrogen release amount, as well as decomposition and nitrogen release efficiency at various stages, were affected by irrigation method, straw type, and their interactions. Overall, decomposition and nitrogen release were highest under flooding irrigation, followed by alternate wetting and drying irrigation. However, under dry farming, the rates of straw decomposition and nitrogen release were relatively moderate, maintaining higher decomposition and nitrogen release amounts even in later stages. Comparing the two straw types, wheat and rapeseed straw showed little difference in nitrogen release amount and rate during early growth stages, but wheat straw showed significantly increased nitrogen release amount and rate during middle and late growth stages. These results

differ from Wu et al.[12], possibly because during straw mulching and return, decomposition proceeds gradually from the parts near the soil surface upward, and thus is influenced by soil contact area, soil physicochemical environment, and mulching layer thickness. Analysis of the optimized straw mulching-nitrogen management pattern (i.e., basal fertilizer:tillering fertilizer:panicle fertilizer ratio of 3:3:4) revealed that this pattern concentrated the peak decomposition period during the tillering stage. The allelopathic effect of straw decomposition reduced rice tiller emergence while significantly promoting belowground root growth. Comparison of decomposition and nitrogen release showed that they were not absolutely positively correlated, indicating that besides the above factors, environmental factors such as water immersion and rainfall leaching also significantly influenced nitrogen release.

### **3.2 Effects of Irrigation Method and Straw Mulch-Nitrogen Management Pattern on Rice Plant Growth**

Soil moisture is one of the most important factors affecting rice root growth; therefore, different irrigation patterns significantly influence root development. Yang et al.[13] reported that alternate wetting and drying irrigation and controlled water irrigation significantly increased rice root activity by an average of 23.7% and 37.9% compared with flooding irrigation. Zeng et al.[14] also found that moist irrigation increased root density during late rice growth stages. However, under straw return conditions, the effects of irrigation patterns on straw decomposition and nutrient release patterns created differences from the effects observed without straw mulching. For example, Zhang et al.[15] demonstrated that straw return under flooding irrigation increased accumulation of reductive toxic substances and reduced soil aeration compared with alternate wetting and drying irrigation, thereby decreasing rice root activity. This study showed that flooding and alternate wetting and drying irrigation significantly increased root dry weight, but flooding irrigation also increased root-shoot ratio. Under flooding and alternate wetting and drying irrigation, wheat straw mulching combined with nitrogen management at a basal fertilizer:tillering fertilizer:panicle fertilizer ratio of 3:3:4 reduced early-stage biomass accumulation but significantly increased accumulation during middle and late growth stages compared with no straw mulching, further confirming the inhibitory effect of straw decomposition on rice during early growth stages. Under dry farming, rapeseed straw combined with the 3:3:4 nitrogen management ratio was significantly higher than wheat straw mulching and no straw mulching, while other treatments showed significant reductions. This may be because the high mass and volume of full rapeseed straw return caused more severe inhibitory effects on rice than wheat straw mulching during the rapid early decomposition stage, which was further exacerbated under flooding irrigation, alternate wetting and drying irrigation, and humid climatic conditions. However, under dry farming, the high straw mass and volume presented certain advantages by providing soil moisture retention and cooling effects during hot, dry weather, thereby ensuring normal plant physiological activities, improving late-stage root growth and root activity, and

increasing late-stage dry matter accumulation and yield formation[16]. Furthermore, this study demonstrated that optimized straw mulch-nitrogen management patterns under all irrigation methods effectively regulated aboveground and belowground rice growth, significantly increasing grain yield. However, the performance of wheat straw and rapeseed straw combined with optimized nitrogen management differed among irrigation methods: wheat straw mulching produced the most significant yield increase under flooding and alternate wetting and drying irrigation, while rapeseed straw mulching was optimal under dry farming, with both showing significant increases in effective panicle number and thousand-grain weight. Water use efficiency was also improved by optimized straw mulch-nitrogen management, particularly with wheat straw mulching under alternate wetting and drying irrigation and rapeseed straw mulching under dry farming, which significantly enhanced water productivity.

### **3.3 Effects of Irrigation Method and Straw Mulch-Nitrogen Management Pattern on Rice Nitrogen Accumulation and Use Efficiency**

Different irrigation methods have produced conflicting results regarding rice nitrogen uptake and use efficiency. Chen et al.[17] reported that flooding irrigation significantly increased plant nitrogen accumulation, nitrogen use efficiency, and nitrogen fertilizer recovery rate compared with controlled irrigation. However, Pan et al.[18] found that alternate wetting and drying irrigation significantly increased total nitrogen uptake and nitrogen use efficiency compared with conventional flooding irrigation, with total nitrogen uptake increasing by 18.5% and 22.1%. Wang et al.[5] demonstrated that wheat straw mulching without a water layer significantly increased plant nitrogen, phosphorus, and potassium uptake, with total nitrogen accumulation increasing by 6.8%-12.6% compared with no straw mulching. This study showed that both alternate wetting and drying and flooding irrigation significantly improved total nitrogen accumulation, nitrogen use efficiency, and nitrogen recovery efficiency compared with dry farming, and alternate wetting and drying irrigation significantly increased nitrogen accumulation at all growth stages compared with other irrigation methods. However, during middle growth stage, nitrogen accumulation under dry farming was significantly higher than under flooding irrigation, differing from previous studies. This suggests that the good temperature-maintaining and moisture-retaining effects of straw mulching, along with moderate straw decomposition and nitrogen release, promoted rice growth and root activity, thereby enhancing nitrogen accumulation. Additionally, under both flooding and alternate wetting and drying irrigation, wheat straw mulching combined with nitrogen management at a 3:3:4 ratio significantly increased plant nitrogen accumulation and nitrogen use efficiency, whereas rapeseed straw mulching significantly reduced these parameters under flooding and alternate wetting and drying irrigation but was optimal under dry farming. This may be because the high mass and volume of full rapeseed straw return further reduced soil temperature under flooding and alternate

wetting and drying irrigation, and the moist environment accelerated massive rapeseed straw decomposition, leading to accumulation of harmful substances, reduced root activity, and slower root growth, thereby slowing nitrogen uptake and ultimately significantly reducing nitrogen accumulation.

### 3.4 Relationship Between Straw Decomposition, Nitrogen Release and Rice Yield, Nitrogen Uptake and Utilization

The effects of straw mulching on rice growth can be divided into direct and indirect impacts. Direct effects include the release of nutrients such as nitrogen, phosphorus, potassium, and micronutrients from straw decomposition, while indirect effects involve changes in soil microbial community structure during straw decomposition that subsequently affect rice growth[19 24]. However, the effects of straw decomposition and nutrient release vary across rice growth stages, showing negative correlations with rice growth during early stages but significant positive correlations with growth and yield during middle and late stages[20 24]. Based on correlation analysis combining aboveground and belowground plant growth and nitrogen accumulation with straw decomposition and nitrogen release across treatments, this study further analyzed the effects of straw decomposition and nitrogen release on rice growth at different stages. Straw decomposition amount at various stages had minor effects on rice yield and nitrogen uptake but significantly affected root-shoot ratio, particularly at 30 DAT and heading stage. However, these effects were non-corresponding, suggesting that straw decomposition primarily influences rice growth through indirect pathways affecting aboveground and belowground development. Overall, large or rapid nitrogen release from straw during 20 and 30 DAT was detrimental to rice growth, whereas nitrogen release at heading and maturity stages significantly or highly significantly promoted rice yield and nitrogen uptake and utilization. Additionally, straw nitrogen release at various stages significantly affected root-shoot ratio, indicating that straw nitrogen release not only directly influenced nitrogen uptake at different stages but also indirectly affected aboveground and belowground growth, thereby influencing rice yield and nitrogen utilization. Therefore, coordinating straw decomposition amount and nitrogen release at different rice growth stages, particularly nitrogen release at 30 DAT, is one of the important measures to ensure high rice yield and high efficiency.

### Conclusion

Alternate wetting and drying irrigation can effectively coordinate rice root growth at various stages, promote nitrogen uptake and utilization, increase grain yield, and improve water productivity, followed by flooding irrigation. However, for straw decomposition and nitrogen release, wheat and rapeseed straw showed significantly higher decomposition and nitrogen release under flooding irrigation than under the other two irrigation methods. Comparing different straw mulching and optimized nitrogen management patterns, at a nitrogen application rate of  $135 \text{ kg} \cdot \text{hm}^{-2}$ , wheat straw mulching combined with

optimized nitrogen management at a basal fertilizer:tillering fertilizer:panicle fertilizer ratio of 3:3:4 showed clear advantages across all irrigation methods, representing the best management model in this experiment. Rapeseed straw combined with this optimized nitrogen management showed strong advantages only under dry farming, providing a reference for implementing straw return in water-scarce regions. Correlation analysis between straw mulching, nitrogen release, and various rice growth factors indicated that coordinating nitrogen release at 30 DAT and later stages can effectively improve rice yield and nitrogen uptake and utilization.

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