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Enhancing rice yield, quality, and resource utilisation with slow-release fertiliser in alternate wetting and drying irrigation

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Abstract: Partial slow-release fertiliser substitution for urea combined with water-saving irrigation may synergistically improve rice yield, quality, water, and nitrogen (N) utilisation. A field experiment to evaluate different combinations of irrigation regimes: alternate wetting and drying irrigation (AWD) and flooding irrigation (FI), and N strategies: N0 (no N fertiliser); N1 (100% conventional fertiliser); N2 (100% SCF – sulphur-coated fertiliser); N3 (70% SCF + 30% urea), and N4 (50% SCF + 50% urea) on efficient rice production. Results indicated that higher substitution rates of SCF (N2 and N3) increased total N and ammonia N in surface water, leachate, and soil while reducing nitrate N relative to N1. The N3 strategy showed the highest yields, dry matter, total N uptake, and water N utilisation due to a nutrient release pattern that matched rice growth requirements. AWD yielded 5% lower than FI, except for the N3 strategy, but protein content increased by 12%, and amylose content dropped by 17%. The structural equation model analysis suggested that SCF positively impacted yield by influencing surface water total N and soil total N. Our findings indicate that implementing AWD alongside a 70% SCF basal fertiliser and 30% urea topdressing can optimise rice yield and quality while effectively managing water and fertiliser resources in the middle-lower Yangtze River Basin.

Keywords: *Oryza sativa* L.; rice sustainable production; nutrition; fertilisation; SEM model

Rice (*Oryza sativa* L.), a staple food crop of global significance, contributes to approximately 20% of per capita energy and 13% of protein consumption globally (Sautter et al. 2006). As a major rice-producing country, China accounts for 18% of the rice planting area and 28% of global rice production, utilising 65%

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of national agricultural water and 14% of fertiliser (Hua et al. 2023). Excessive nitrogen (N) fertiliser use in China leads to significant environmental deterioration and low N utilisation efficiency (NUE). Moreover, meeting the growing demand for flavour and nutritional quality rice requires the development of sustainable and efficient rice production methods (Ishfaq et al. 2021). Fortunately, studies have shown that targeted and efficient water and fertiliser management can achieve objectives such as high yield, quality, and NUE (Ye et al. 2013, Cao et al. 2021).

Alternate wetting and drying irrigation (AWD), a widely implemented practice in rice-growing nations (Lampayan et al. 2015), reduced water consumption for irrigation and, importantly, no significant reduction or even potential increase in rice yields (Zhang et al. 2021). AWD improves air exchange between the soil and atmosphere, leading to a more muscular root system and enhanced nutrient uptake by the crop (Tan et al. 2013). It also creates alternating wet and dry conditions in the topsoil, affecting N transport and possibly increasing nitrification, which can result in N loss (Shekhar et al. 2021). Additionally, AWD improves soil nutrient levels, increases oxygen content, enhances ammonia assimilation enzyme activity, stimulates root hormone secretion, and promotes root vigour (Zhang et al. 2021). These factors contribute to improved grain filling, delayed plant senescence, and enhanced leaf photosynthetic performance, ultimately increasing dry matter, yield, and total N uptake (Sun et al. 2023).

Fertilisation strategies are crucial in determining crop yields and major input in rice production. Slow-release fertilisers are recognised as a practical approach to enhancing grain yield and NUE in crops due to the slow release of nutrients from the fertiliser, which reduces nutrient loss and lowers labour costs compared to conventional fertiliser (CF) (Hua et al. 2023). In the market, slow-release fertilisers mostly rely on coating technology. They can be classified into two main categories: insoluble inorganic coating materials (such as sulphur) and petroleum-based coating materials (such as polyethene, polypropylene, and polyvinyl chloride) (Wei et al. 2020). In the laboratory, researchers are increasingly studying alternative coating materials derived from renewable resources like starch-based, lignin, and cellulose; these materials show promising applications in agriculture and industry due to their environmental friendliness and cost-effectiveness (Chen et al. 2023, Duan et al. 2023). However, the efficacy of slow-release fertilisers can vary under different water and fertiliser management practices due to factors such as coating material, thickness, moisture, fertilisation pattern, temperature, and microbial activity (Sun et al. 2023). In the context of paddy rice cultivation in southern China, it is essential to investigate the nutrient-release characteristics of slow-release fertilisers under high moisture conditions and evaluate their potential for enhancing efficient and sustainable rice production.

Compared to CF, although slow-release fertilisers have a more extended availability, applying slow-release fertilisers alone as a basal fertiliser may not sufficiently meet the nutrient requirements during later growth stages, which can result in excessive N content in the soil and water during the early growth stages (Ding et al. 2018). Increased N levels can lead to amplified drainage, leaching, and the emergence of unproductive rice tillers, ultimately reducing NUE (Zhang et al. 2021, Hua et al. 2023). To address these gaps, applying a proportion of slow-release fertilisers basal fertilisers, and urea topdressing fertiliser is an efficient strategy (Shi et al. 2023), but determining the optimal proportion of slow-release fertilisers and urea rate remains challenging as it is influenced by factors such as region, type of slow-release fertilisers, release rate, and rice cultivar (Sun et al. 2023). Under the AWD regime, applying a substitution of slow-release fertilisers can achieve comparable nutrient levels to those attained with complete slow-release fertilisers under flooding irrigation (FI), thanks to the higher nutrient concentration facilitated by lower water levels in the paddy field.

Therefore, we hypothesise that combining AWD and slow-release fertilisers substituting urea can synergistically improve yields, water and N utilisation, and rice quality. This study investigates the impacts of irrigation regimes (AWD and FI) combined with slow-release fertilisers and CF rates on various parameters, including N concentrations in surface and leachate water, soil N content, rice dry matter, total N uptake, and grain yield and quality. We aim to identify the most promising approaches for sustainable rice cultivation in the middle-lower Yangtze River Basin.

MATERIAL AND METHODS

Experimental site. The field experiments were conducted from May to September 2022 at the Hubei Irrigation Experimental Centre Station (30°54'23"N,

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112°05'16"E) in Jingmen City, Hubei Province, China. This region is in a subtropical monsoon climate zone, with an average annual temperature of approximately 17 °C, a yearly precipitation of about 947 mm, and an annual average evaporation capacity of about 1 231.2 mm. The area experiences a perennial sunshine duration of 1 300–1 600 h and an average frost-free period of 206 days. The soil type was classified as Cambisols (IUSS Working Group WRB 2006) by the WRB system, with a silt loam texture classification (14.09% sand + 70.76% silt + 15.15% clay). The soil (0–20 cm) at the trial plot had 1.49 g/cm^3 bulk density, 4.55 g/kg organic carbon, 7.71 pH, 1.41 g/kg total N, 19.2 mg/kg available phosphorus (P), and 120 mg/kg available potassium (K).

Experimental design and field management. The experiment was designed as two irrigation methods, AWD and FI, and five N strategies: N0 – 0 kg N/ha; N1 – 100% CF; N2 – 100% sulphur-coated fertiliser (SCF); N3 – 70% SCF + 30% CF; N4 – 50% SCF + 50% CF. These ten water and N treatments, with three replications of each field for 30 experimental plots of 36 m^2 (6 m × 6 m), were tested in a split-plot design.

The water depth control criteria have been described in Hua et al. (2023). Each plot was managed with individual irrigation and drainage systems, and the field's water depth was measured using a fixed scale. The amount of irrigation water was recorded using a water meter, while the drainage amount was calculated based on the difference in water level before and after drainage. The N application rate for all N treatments (except N0) was 180 kg N/ha (as pure N). The N1 strategy was divided into two applications, with 50% ammonium bicarbonate applied as a basal fertiliser and the remaining 50% urea applied as a topdressing fertiliser. For the N2 strategy, the SCF was solely utilised as the basal fertiliser, with an application rate of 720 kg/ha (to fulfil the 180 kg N/ha requirement of pure N). The SCF, a typical slow-release fertiliser (purchased from Hubei Sanning Chemical Co., Ltd, Hubei, China), had a nutrient release period of approximately 3 to 4 months. Regarding the N3 and N4 strategy, a two-split application approach was adopted. 70% (N3) or 50% (N4) of the N was provided by SCF as the basal fertiliser, with urea supplying the remaining N for topdressing (Table 1). P and K fertilisers were applied at 18.7 kg P/ha and 54 kg K/ha as basal fertilisers in all treatments. Calcium superphosphate and potassium chloride were necessary for all treatments except the N2 strategy to fulfil the required P and K dose rates, as detailed in Table 1. The basal fertiliser was surface broadcasted one day before rice transplanting, and the topdressing fertiliser was applied in the same way 15 days later.

The seedlings were transplanted on May 21st at a spacing of 30 cm × 25 cm, with three seedlings per plant, and harvested on September 1st. The hybrid rice cv. Zuanliangyouchaozhan, which is used in this study, is widely grown locally. All other field management practices remained consistent with the customary methods employed by local farmers.

Water sample collection and analysis. Water samples were collected from two depths: the field surface and leachate. Before rice transplanting, PVC pipes were buried at a depth of 20 cm in each plot. Field surface water was collected by randomly selecting five points within the plot and combining the samples in polyethene bottles. Leachate was extracted from the buried PVC pipes using a handheld pump. Sampling occurred on the 1st, 3rd, 5th, 7th, and 9th days after fertiliser application (basal

Table 1. Fertilisation schemes for rice under the five nitrogen management strategies

Treatment	Fertilisers (N:P:K, kg/ha)	Basal application (kg/ha)				Topdressing application (kg/ha) CU
		sulphur-coated fertiliser	ammonium bicarbonate	calcium superphosphate	potassium chloride	
N0	0:18.7:54	0.0	0.0	360.0	108.0	0.0
N1	180:18.7:54	0.0	526.3	360.0	108.0	195.7
N2	180:18.7:54	720.0	0.0	0.0	0.0	0.0
N3	180:18.7:54	504.0	0.0	108.0	32.4	117.4
N4	180:18.7:54	360.0	0.0	108.0	54.0	195.7

N0 – no N fertiliser; N1 – 100% conventional fertiliser (CF); N2 – 100% sulphur-coated fertiliser (SCF, N-P-K = 25%-2.6%-7.5%, nutrient content ≥ 35.1%); N3 – 70% SCF + 30% CF; N4 – 50% SCF + 50% CF; CU – conventional urea (46% N), ammonium bicarbonate (17% N), calcium superphosphate (5.2% P), and potassium chloride content (49.8% K)

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and topdressing). Additional water samples were taken when field drainage occurred due to rainfall. The sampling frequency for the N0 (no N fertiliser application) and N2 (basal fertiliser only) treatments and other N strategies remained consistent for comparative analysis. Water samples were analysed for total N (TN), ammonium N (NH_4^+-N), and nitrate N (NO_3^--N). The ultraviolet spectrophotometric method determined TN concentration by alkaline potassium persulfate digestion. After filtration through a 0.45 µm filter paper, NH_4^+-N concentrations were measured by Nessler's reagent colourimetry method and NO_3^--N concentrations by the ultraviolet spectrophotometry method.

Plant and soil sample collection and analysis. Three representative plants were selected from each plot at various rice growth stages, namely late tillering, heading flowering, milk ripening, and yellow ripening stages. The plants were divided into stem, leaf, and panicle parts and subsequently subjected to drying at 105 °C for 2 h, followed by further drying at 85 °C until a constant weight was achieved to determine the dry matter. Soil samples were collected from 0–20 cm depths at five points within each plot. Soil collection occurred at early tillering, late tillering, heading flowering, milk ripening, and yellow ripening stages. A portion of the freshly collected soil samples was immediately refrigerated at –20 °C for subsequent analysis of NH_4^+-N and NO_3^--N content, while the remaining samples were air-dried to determine TN. The laboratory determined the NH_4^+-N and NO_3^--N content using the 1 mol/L potassium chloride extraction-spectrophotometry method. Plant tissues and air-dried soil samples were finely ground and sieved, and the semi-micro Kjeldahl N determination method was used to assess the TN concentration. Grain yield was determined based on a moisture content of 14% after air-drying the grains for three days in a randomly selected area of 3 m^2 within each plot during the yellow ripening stage.

Grain amylose and protein content. A 100 mg sample of air-dried rice grains, which were dehulled and stored for three months, underwent milling and sieving procedures before determining amylose and protein content. The amylose content was assessed by staining it with an iodine reagent and then measuring it using an autoanalyser system (DPCZ-II, Hangzhou, China). The samples were shaken in 0.1 mol/L NaOH for 1 h to extract proteins. Following centrifugation, the supernatant was combined with Coomassie Brilliant Blue G250, and its optical density was measured at 595 nm using an ultraviolet spectrophotometer. The protein content was then calculated using a calibration curve for bovine serum albumin (Kenawy et al. 2021).

Water use efficiency and nitrogen utilisation efficiency Water use efficiency (WUE) indicators were calculated as follows:

$$WUE_i\ (kg/m^3) = \frac{Y\ (kg/ha)}{I\ (m^3/ha)} \qquad (1)$$

$$WUE_b\ (kg/m^3) = \frac{DM\ (kg/ha)}{ET_c\ (m^3/ha)} \qquad (2)$$

Where: Y – grain yield; DM – dry matter; ET_c – actual evapotranspiration; I – amount of irrigation; WUE_i – WUE for irrigation; WUE_b – WUE for biomass.

The following formula calculated the NUE:

$$NHI\ (\%) = \frac{TNU_{grain}}{TNU} \qquad (3)$$

$$REN\ (\%) = \frac{TNU - TUN_{ck}}{applied\ N\ (kg/ha)} \qquad (4)$$

$$REN\ (\%) = \frac{TNU - TUN_{ck}}{applied\ N\ (kg/ha)} \qquad (5)$$

$$AEN\ (kg/ha) = \frac{Y - Y_{ck}}{applied\ N} \qquad (6)$$

$$PFP_n\ (kg/kg) = \frac{Y}{applied\ N} \qquad (7)$$

Where: TNU – total N uptake; DM_i – dry matter of stem, leaf, or panicle; C_i – N content of stem, leaf, or panicle; TNU_{grain}, TNU_{ck}, and Y_{ck} – TNU in grain and unfertilised plots, and the yield in unfertilised plots, respectively; NHI, REN, AEN, and PFP_n – N harvest index, N recovery efficiency, agronomic use efficiency of N fertiliser, and N partial factor productivity, respectively.

Statistical analyses. An analysis of variance (ANOVA) was conducted in this study to investigate the effects of irrigation regimes, N strategies, and their interaction on various parameters. Duncan's test ($P < 0.05$) was employed to compare the mean values of different treatments. IBM SPSS Statistics 26.0 software (IBM Corp., Armonk, USA) was utilised for statistical analyses. A structural equation model (SEM) was performed using the lavaan packages in the R language. Before implementing the lavaan packages, the weighted average values of water and soil TN, total N uptake, and dry matter were calculated using the trapezoid area method (Durán et al. 2014). Tables and graphs were drawn using Excel (Microsoft Window, Redmond, USA) and Origin 2021 (Originlab, Northampton, USA).

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RESULTS AND DISCUSSION

The impact of the N strategy on N content in water and soil outweighed that of the irrigation regime (Table 2). Surface water TN, NH_4^+-N, and NO_3^--N were higher under the high substitutions of SCF than the N1 strategy, while N4 was lower than N1. The higher concentrations under SCF were due to the higher N application during the basal fertiliser than N1 (N2, N3, and N1 are 180, 126, and 90 kg/ha of pure N, respectively). In leachate and soil, NO_3^--N concentrations were significantly higher in the N1 than in the SCF strategy. The higher fixation of NH_4^+-N by SCF slowed urea's ammonification and hydrolysis processes, thus reducing potential early-stage nitrification (Shi et al. 2023).

The high substitutions SCF (N2, N3) strategy significantly increased the dry matter of the stem and panicle (Table 3). In contrast, increasing dry matter mass under the N4 strategy was insignificant compared to N1. The pattern of total N uptake aligned consistently with the dry matter trend. The N3 strategy had the highest weighted average total N uptake value, showing a remarkable 14% increase compared to N1. Utilising SCF facilitates the maintenance of an optimal equilibrium between the intensity of nutrient supply and the physiological demands of the crop, consequently fostering enhanced plant height, leaf area index, and dry matter accumulation (Zhang et al. 2021, Yu et al. 2022). Notably, the N3 strategy synergistically increased dry matter and total N uptake, whose positive effect was further enhanced under the AWD regime. Previous studies have also observed a similar phenomenon, mainly attributing it to the fact that 70% of SCF served as a basal fertiliser to meet rice's N requirements, while 30% of urea was applied during the tillering stage to compensate for any N deficiency caused by SCF in the later stage (Ding et al. 2018, Yu et al. 2022). Meanwhile, the AWD regime improved the air environment and promoted root growth, increasing dry matter and total N uptake accumulation (Tan et al. 2013).

The N strategy and the interaction between the irrigation regime and the N strategy significantly influenced grain yield. Figure 1A demonstrates that the results did not consistently increase with changing N strategies (N0 to N4); instead, the highest yields

Table 2. Effects of various treatments on weighted average total nitrogen (TN), ammonium nitrogen (NH_4^+-N), and nitrate nitrogen (NO_3^--N) in surface and leachate water and soil

Treatment	Surface water N			Leachate water N			Soil N		
	TN	NH_4^+-N	NO_3^--N	TN	NH_4^+-N	NO_3^--N	TN (g/kg)	NH_4^+-N	NO_3^--N
	(mg/L)							(mg/kg)	
Irrigation regimes									
FI	6.69^b	3.30^b	0.28^a	9.64^a	5.62^a	1.12^a	0.60^a	3.99^a	1.31^a
AWD	7.55^a	4.70^a	0.33^a	8.76^a	5.29^a	0.97^a	0.56^a	4.08^a	1.36^a
Nitrogen strategies									
N0	1.72^d	0.77^c	0.17^b	1.55^c	0.82^c	1.37^a	0.41^b	3.34^c	1.17^b
N1	8.18^{bc}	5.10^a	0.34^a	8.73^b	5.61^b	1.30^a	0.59^a	4.28^{ab}	1.55^a
N2	9.83^a	5.41^a	0.36^a	15.12^a	9.46^a	0.93^b	0.57^a	4.58^a	1.34^b
N3	8.67^{ab}	5.79^a	0.38^a	10.37^b	6.45^b	0.80^c	0.65^a	4.02^b	1.38^a
N4	7.19^c	2.94^b	0.28^a	10.22^b	4.93^b	0.84^c	0.68^a	3.96^b	1.24^b
***F*-values**									
I	10.55**	20.74***	3.41	0.36	0.21	2.91	1.97	0.58	1.02
N	114.64***	37.85***	8.07***	8.85***	14.45***	36.33**	7.90**	10.65***	7.52**
I × N	7.52**	9.64***	2.98	0.26	0.69	4.26*	1.58	14.00***	4.65**

FI – flooding irrigation; AWD – alternate wetting and drying irrigation; N0 – 0 kg N/ha; N1 – 100% conventional fertiliser (CF); N2 – 100% sulphur-coated fertiliser (SCF); N3 – 70% SCF + 30% CF; N4 – 50% SCF + 50% CF; I – irrigation regimes (averaged across nitrogen strategies); N – nitrogen strategies (averaged across irrigation regimes). Values denoted by different lowercase letters within the same main category indicate significant differences ($P < 0.05$, Duncan's test). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

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Table 3. Dry matter of rice stems, leaves, and panicles and total nitrogen uptake under different water and fertiliser management modes

Treatment	Dry matter (t/ha)			Total nitrogen uptake (kg/ha)
	stem	leaf	panicle	
Irrigation regimes				
FI	3.27[b]	1.22[b]	3.59[a]	35.50[a]
AWD	3.55[a]	1.40[a]	3.58[a]	33.20[b]
Nitrogen strategies				
N0	1.26[d]	0.40[b]	1.05[c]	12.97[d]
N1	3.47[c]	1.42[a]	3.68[b]	37.21[c]
N2	4.20[ab]	1.55[a]	4.59[a]	40.07[ab]
N3	4.43[a]	1.69[a]	4.60[a]	42.35[a]
N4	3.70[bc]	1.48[a]	3.99[ab]	39.16[bc]
***F*-values**				
I	12.56**	7.57*	0.08	9.05**
N	197.36***	52.97***	37.51***	200.20***
I × N	28.47***	3.48*	0.72	6.01**

FI – flooding irrigation; AWD – alternate wetting and drying irrigation; N0 – 0 kg N/ha; N1 – 100% conventional fertiliser (CF); N2 – 100% sulphur-coated fertiliser (SCF); N3 – 70% SCF + 30% CF; N4 – 50% SCF + 50% CF; I – irrigation regimes (averaged across nitrogen strategies); N – nitrogen strategies (averaged across irrigation regimes). Values denoted by different lowercase letters within the same main category indicate significant differences (P < 0.05, Duncan's test). *P < 0.05; **P < 0.01; ***P < 0.001

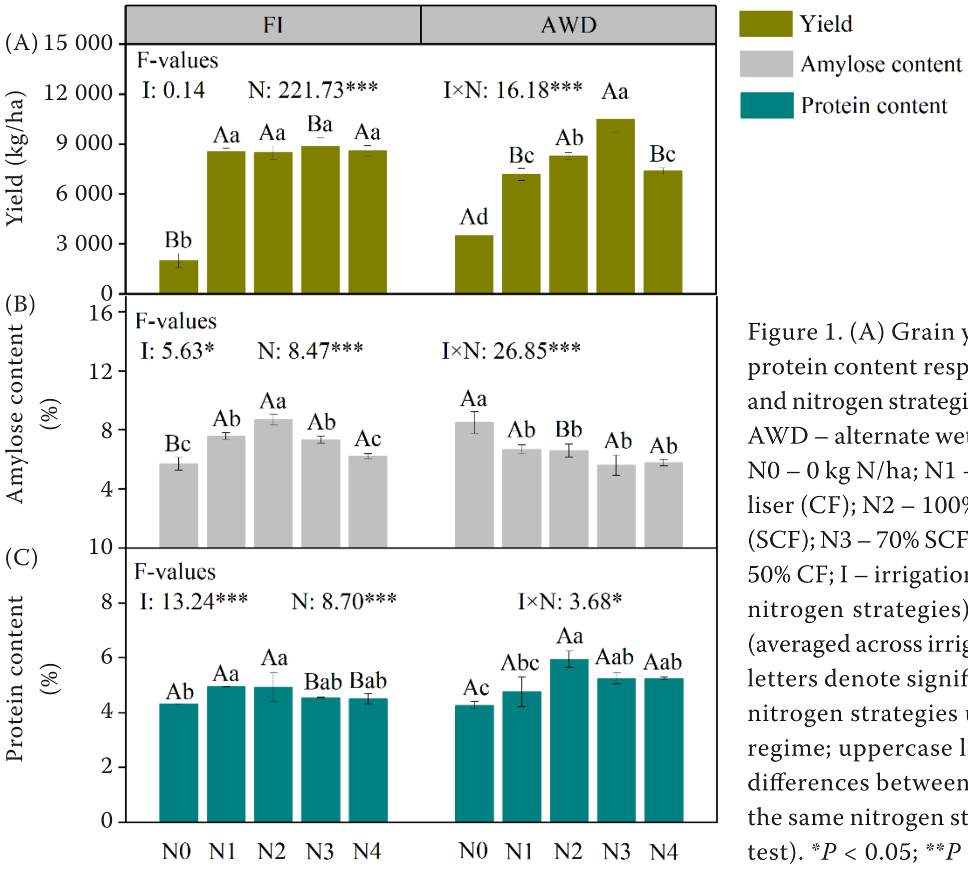

Figure 1. (A) Grain yield; (B) amylose, and (C) protein content response to irrigation regimes and nitrogen strategies. FI – flooding irrigation; AWD – alternate wetting and drying irrigation; N0 – 0 kg N/ha; N1 – 100% conventional fertiliser (CF); N2 – 100% sulphur-coated fertiliser (SCF); N3 – 70% SCF + 30% CF; N4 – 50% SCF + 50% CF; I – irrigation regimes (averaged across nitrogen strategies); N – nitrogen strategies (averaged across irrigation regimes). Lowercase letters denote significant differences between nitrogen strategies under the same irrigation regime; uppercase letters indicate significant differences between irrigation regimes under the same nitrogen strategy (P < 0.05, Duncan's test). *P < 0.05; **P < 0.01; ***P < 0.001

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were observed under the N3 strategy, particularly under the AWD regime. The mechanism underlying the yield increase in the SCF could be attributed to the rise in the adequate number of spikes per square meter, dry matter and total N uptake, and associated enzyme activities (Table 3; Sun et al. 2012, Hua et al. 2023). Previous studies have indicated that the optimal proportion of SCF to CF is 7:3, as exceeding this ratio resulted in a decline in yield (Ding et al. 2018, Zhang et al. 2021, Yu et al. 2022). Besides, the FI yielded higher than the AWD in all cases except when combined with the N3. This difference may be attributed to the high temperature experienced in 2022 (Jiang et al. 2023), where adequate moisture helps mitigate the negative impact of high temperatures on yield.

For amylose content, applied N treatments were significantly decreased by an average of 17% under AWD compared to FI (Figure 1B). The change in amylose content was more strongly under FI than AWD, with a substantial 28% decrease observed under the N4 compared to the N2. Conversely, the protein content of applied N treatments saw a significant 12% increase under AWD compared to FI, and it consistently decreased with a declining proportion of SCF (Figure 1C). Suitable drought conditions can effectively reduce amylose content in rice by suppressing the expression of the *Wx* gene, which is responsible for amylose synthesis. Conversely, the FI regime has been found to increase amylose content and decrease protein content in rice (Yang et al. 2019). The N3 strategy resulted in the highest protein content and lowest amylose content, leading to improved rice flavour and nutritional quality. This trade-off is attributed to the enhanced N metabolism, which tends to restrain carbon metabolism during grain filling. It was observed that 70% SCF + 30% urea was beneficial in increasing protein fractions while reducing the levels of amylose, amylopectin, and starch contents during the later stages of the rice (Wei et al. 2018).

The interaction between water and fertiliser significantly impacted WUE, particularly in AWD combined with the N3 treatment, where WUE was notably increased (Figure 2, Table 4). It could be attributed to the substantial increase in biomass under the AWD + N3 condition, resulting in improved canopy cover and reduced canopy temperature (Zhang et

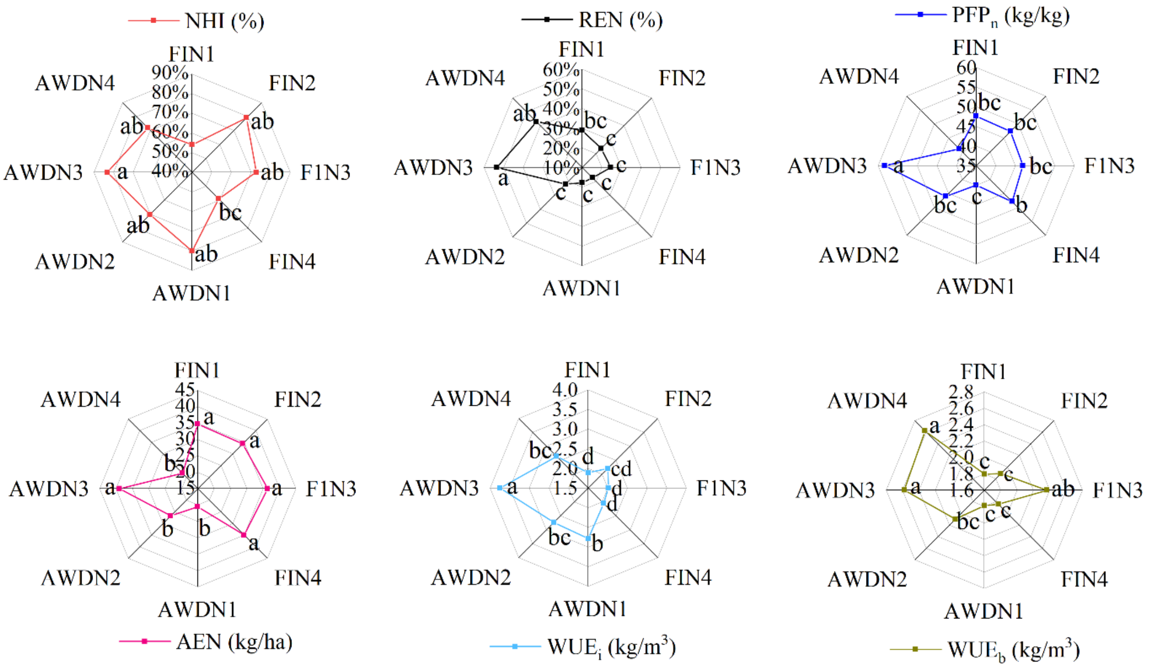

Figure 2. Nitrogen harvest index (NHI); nitrogen recovery efficiency (REN); nitrogen partial factor productivity (PFP_n); agronomic use efficiency of nitrogen fertiliser (AEN); water use efficiency for irrigation (WUE_i), and water use efficiency for biomass (WUE_b) in response to different water and fertiliser management modes. FI – flooding irrigation; AWD – alternate wetting and drying irrigation; N1 – 100% conventional fertiliser (CF); N2 – 100% sulphur-coated fertiliser (SCF); N3 – 70% SCF + 30% CF; N4 – 50% SCF + 50% CF. Different lowercase letters denote significant variations within the same main category at a significance level of 5%

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Table 4. Analysis of irrigation regime and nitrogen strategy on nitrogen harvest index (NHI); nitrogen recovery efficiency (REN); nitrogen partial factor productivity (PFP_n); agronomic use efficiency of nitrogen fertiliser (AEN); irrigation water use efficiency (WUE_i), and biomass water use efficiency (WUE_b)

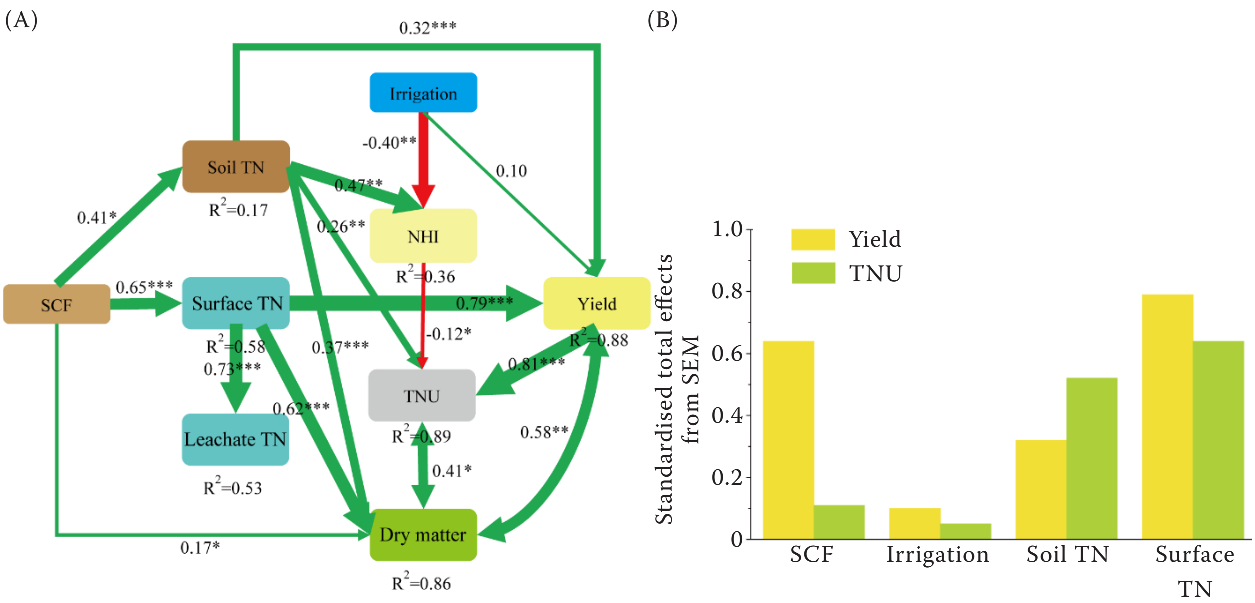
	NHI	REN	PFP_n	AEN	WUE_i	WUE_b
***F*-values**						
I	6.57*	21.90***	0.85	69.10***	64.87***	11.45**
N	2.27	11.94***	12.19***	21.41***	4.85*	10.93**
I × N	3.42*	22.43***	14.63***	15.14***	5.81**	3.55*

I – irrigation regimes (averaged across nitrogen strategies); N – nitrogen strategies (averaged across irrigation regimes). *P < 0.05; **P < 0.01; ***P < 0.001

al. 2023). These factors ultimately enhanced crop WUE, especially during the extreme drought in the middle-lower Yangtze River Basin in 2022 (Jiang et al. 2023).

The irrigation regime and N strategy and their interaction significantly influenced the REN, PFP_n, AEN, WUE_i, and WUE_b. In contrast, the N strategy's impact on NHI was insignificant (Table 4). Although overall N uptake in the unfertilised and conventional fertiliser treatments was lower than SCF, N transport efficiency from nutrient organs to rice grains may be constrained by the chosen N strategy (Sun et al. 2023). All applied N treatments (except the N3 strategy) of NHI, REN, WUE_i, and WUE_b were higher under the AWD than the FI. However, PFP_n and AEN exhibited higher values under the FI, which can be attributed to the superior grain yields observed with the FI.

As shown in Figure 3, the SEM illustrates the impacts of SCF, irrigation, and TN in water and soil on yield and total N uptake. The findings indicate that both soil TN (0.32***) and surface water TN (0.79***) exerted a direct positive influence on yield (Figure 3A). SCF significantly contributed to a positive effect of 0.64 on yield, directly affecting surface water TN



χ^2/df = 0.83; P = 0.654; GFI = 0.912; CFI = 0.997; RMSEA = 0.004

Figure 3. (A) The structural equation model (SEM) for the effects of sulphur-coated fertiliser (SCF) proportion, irrigation volume, and total nitrogen content of water and soil (i.e., surface TN, leachate TN, and soil TN) on yield and total N uptake (TNU), and (B) standardised total effects from SEM. NHI – nitrogen harvest index. Green and red arrows indicate positive and negative relationships, respectively. The arrow's width is proportional to the strength of the path coefficient. Only explanatory and underlying variables with significant factor loadings were considered in the SEM analysis, while non-significant pathways were excluded. The significant levels were *P < 0.05; **P < 0.01; ***P < 0.001

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and soil TN. Yield and soil TN directly influenced total N uptake, while NHI harmed it. Among the factors, field water TN exhibited the highest total effect on total N uptake (0.64***), followed by soil TN (0.52***) (Figure 3B).

In this work, high SCF substitutions (N2 and N3 strategies) increased TN and NH_4^+-N concentrations while reducing NO_3^--N concentrations in the rice tillage layer. The N3 strategy exhibited superior dry matter, total N uptake, yield, quality, water, and N utilisation compared to other N strategies. Although AWD decreased rice yield compared to FI, it increased protein content, reduced amylose content, and ultimately improved rice quality. The SEM results indicated high SCF substitutions directly influenced surface water and soil N content, increasing rice yield, total N uptake, and dry matter. High SCF substitutions for urea synergistically increased rice yield, quality, and resource efficiency, while low SCF substitutions were counterproductive. Interestingly, an SCF:CF of 7:3 maximised these benefits, particularly when combined with AWD. Based on these findings, we recommend utilising 70% SCF basal fertiliser and 30% urea topdressing fertiliser under AWD for sustainable and efficient rice production in the middle-lower Yangtze River Basin.

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