



Increasing water productivity, nitrogen economy, and grain yield of rice by water saving irrigation and fertilizer-N management

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Abstract

The looming water resources worldwide necessitate the development of water-saving technologies in rice production. An open greenhouse experiment was conducted on rice during the summer season of 2016 at Huazhong Agricultural University, Wuhan, China, in order to study the influence of irrigation methods and nitrogen (N) inputs on water productivity, N economy, and grain yield of rice. Two irrigation methods, viz. conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSM DI), and three levels of nitrogen, viz. 0 kg N ha⁻¹ (N₀), 90 kg N ha⁻¹ (N₁), and 180 kg N ha⁻¹ (N₂), were examined with three replications. Study data indicated that no significant water by nitrogen interaction on grain yield, biomass, water productivity, N uptake, NUE, and fertilizer N balance was observed. Results revealed that TSM DI method showed significantly higher water productivity and irrigation water applications were reduced by 17.49% in TSM DI compared to CI. Thus, TSM DI enhanced root growth and offered significantly greater water saving along with getting more grain yield compared to CI. Nitrogen tracer (¹⁵N) technique accurately assessed the absorption and distribution of added N in the soil crop environment and divulge higher nitrogen use efficiency (NUE) influenced by TSM DI. At the same N inputs, the TSM DI was the optimal method to minimize nitrogen leaching loss by decreasing water leakage about 18.63%, which are beneficial for the ecological environment.

Keywords Water productivity · Irrigation methods · Grain yield · ¹⁵N tracer · Nitrogen use efficiency · Nitrogen leaching

Introduction

Rice (*Oryza sativa* L.) is a major food crop with more than 50 kg of per capita global annual consumption (FAOSTAT

The original publication of this paper contains a mistake. Correct presentation of Tables 4, 5 and 6 is shown in this article.

The original version of this article was revised.

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2016) and is essential to safeguard global food security. The traditional way of rice production requires higher water input than other cereal crops (Pimentel et al. 2004). Currently, the shortage of water resources is affecting 4 billion population around the world (Mekonnen and Hoekstra 2016); thus, it is inevitable to develop the potential agricultural measures for reducing water usage while maintaining or increasing yield to feed growing world's population (Cerda et al. 2009).

Various irrigation management practices have been suggested to minimize the vast use of fresh water in rice. In relation to previous reports, wetting and drying irrigation could reduce the water input for rice cultivation without jeopardizing grain yield while enhancing water productivity and efficient utilization of nutrients (Wang et al. 2016). Tan et al. (2013) concluded that continuous submergence is not compulsory for paddy field compared with intermittent irrigation. Earlier work demonstrated that intermittent irrigation technology could maintain or even improve the rice grain production, while moderate wetting and drying enhance plant root growth (Zhang et al. 2009). It is still questionable that intermittent irrigation technology enables the dual purpose of grain production and water conservation (Liu et al. 2013).

Nitrogen (N) is another determining factor for crop growth and plays a vital role in maintaining rice production (Spiertz 2010). In order to achieve higher crop productivity, farmers use a lot of chemical nitrogenous fertilizers. The increase of N fertilizer (about 800%) use from 1960 to 2000 in rice, maize, and wheat production accounted about half of the current consumption (Canfield et al. 2010). As the largest consumer of chemical N in the world, China accounts for 32% of the world's total N consumption, and approximately 18% of the chemical N is applied to rice paddies (Heffer 2009).

While the efficiency of N utilization is notoriously low with continuous flooding (Zhang et al. 2012), use of continuous flooding for rice cultivation significantly reduces the rhizosphere redox potential while enhancing the extractable (free) Fe^{+2} concentration and creates an unhealthy environment for root growth and nutrient uptake (Sahrawat 2000; Olaleye et al. 2001; Yang et al. 2004). The plants have extensive root system under water-saving irrigation, as the interval irrigation makes a decent coalition with root system through better provision of oxygen and ultimately improve nutrient uptake (Stoop et al. 2002). It has been reported that wetting and drying irrigation during rice cultivation may reduce the N losses by minimizing the ammonium and T-N leaching, and thus recorded higher NUE (Wang et al. 2011; Zhang et al. 2009). Proper management of water and nitrogen application synergistically improves water productivity and NUE (Cao et al. 2007; Liu et al. 2013; Yang 2015), primarily because of a reduction in unnecessary vegetative growth, which offers a better environment for root growth and canopy development (Yang et al. 2016).

Though the confirmations are rare, expertise to achieve the synergistic effect of water and nitrogen on crop growth is still tacit. Isotopically labeled ^{15}N are supportive to examine the fate of applied N in different organs (Schimel et al. 1989). The ^{15}N tracer is an accurate and reliable technology for estimating fertilizer NUE (Fan et al. 2007; Kongchum et al. 2007; Nishida et al. 2007; Cong et al. 2008).

Despite the availability of abundant literature regarding wetting and drying irrigation as a water-saving technique in paddy environment, the N dynamic triggered by “thin-shallow-moist-dry” irrigation (TSMDI) and the manner by which it accelerated the crop growth responses at different stages under fertilizer N inputs are still not well documented. Thus, it is inevitable to understand the efficiency of fertilizer recovery in paddy soil in order to put up a convincing information. The aim of the present study was to assess the influence of irrigation methods and nitrogen inputs on water productivity, grain yield, and nitrogen economy in the soil crop environment. For this, the ^{15}N tracer technique was used to quantify the N portion accumulated in different parts of the rice plant. Moreover, the influence of water-saving irrigation on the leaching loss of nitrogen was too seen. Such a study could provide valuable facts to achieve higher food production, and resources use efficiency during rice cultivation and may help

in understanding the interplay between water and nitrogen in different process of rice growth and yield formation.

Materials and methods

Experimental conditions

The present study was conducted in the open greenhouse on rice crop (the influence of rainfall was avoided using mobile shelter) at Huazhong Agricultural University, Wuhan, China, during the summer season in 2016. The soil was collected from paddy field of Jingmen in Hubei Province, China (altitude 81.8 m, $112^{\circ}10.823''$ E and $30^{\circ}52.365''$ N) from depths of 0–20 and 20–40 cm. The basic indices of the soil are shown in Table 1.

Soil columns construction

A schematic presentation of the soil column is shown in Fig. 1. The calculated area of soil column was 0.062 m^2 (28 cm in diameter and 50 cm in length). The bottom of the column was wrapped in nylon mesh to prevent interruption through sedimentation and had small holes drilled for leachate collection. To imitate a leaching filter bed, fine quartz sand and small gravels were used in the bottom of each column (from 45 to 50 cm). The topsoil (0–20 cm) and subsoil (20–40 cm) samples from the field were air-dried, passed through a 2-mm sieve, and thoroughly mixed of each original field layer. Then, 18.21 and 18.94 kg soil (according to field top-soil and sub-soil bulk density (Table 1)) were repacked into the corresponding layers of each column and pressed little by a wooden hammer to form a plow bottom (semi-impermeable layer).

Experimental design and treatments

A two-factor factorial experiment based on completely randomized design was conducted with three replications of each treatment. Irrigation factor included two levels: conventional irrigation (CI) and thin-shallow-moist-dry irrigation (TSMDI) and nitrogen factor comprised of three levels: 0 kg N ha^{-1} (N_0), 90 kg N ha^{-1} (N_1), and 180 kg N ha^{-1} (N_2). The TSMDI method was imposed in nine columns. The volume of the individually irrigated column was calculated by graduated cylinder, and the ponded water meters were also set up in each column. In CI method, columns were kept almost in the flooding condition until maturity. The CI treatment was irrigated when ponded water depth became lower than the lower depth limit in specific rice growth stage. Just before panicle initiation, a relatively long period of 10–12 days without ponded water was imposed to impede the excessive rice tillering, which is characterized as mid-season drainage or “sun-baking” (Mao 1993). The standards of irrigation management are listed in Table 2.

Table 1 Soil characteristics in experiment

Soil depth (cm)	Bulk density (g cm ⁻³)	Total porosity (%)	Organic matter (g kg ⁻¹)	Saturated hydraulic conductivity (cm h ⁻¹)	Particle size distribution (%)		
					Sand (2–0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)
0–20	1.46	44.91	19.15	0.8005	21.65	62.68	15.67
20–40	1.53	42.26	7.02	0.3329	23.74	57.20	19.07

Porosity was calculated from soil bulk density using porosity (%) = 1 – (BD/2.65) × 100

The levels of N fertilizer are expressed as N₀ (0 g N column⁻¹), N₁ (0.554 g N column⁻¹), and N₂ (1.108 g N column⁻¹). The ¹⁵N 6% enriched urea was applied in three splits: 50% a basal application, 25% at tillering stage, and 25% at booting stage (Fig. 3: arrows show top dressing). The ¹⁵N-tracer technique was applied to quantify the portion of applied N taken up by different parts of rice. In the present investigation, CI-N₂ represents the practice of irrigation management and nitrogen level adopted by the local farmers. To boot, each column received basal calcium superphosphate at 40 kg ha⁻¹ (4.62 g column⁻¹) and potassium chloride at 70 kg ha⁻¹ (0.84 g column⁻¹) uniformly. All basal fertilizers were incorporated into the soil 1 day before transplanting. Three healthy seedlings of the locally grown rice cultivar “Qi Liang You 908” were planted in each column.

Sampling and analysis

One rice plant in each column was sampled at the tillering, booting, and post-harvest stages. So, two plants of each column were kept on booting stage, and one plant of each column was kept until the end of the experiment. The object of this sampling was to determine the magnitude of translocation of the absorbed top-dressing nitrogen into different plant parts influenced by applied treatments. Plant samples were taken manually during successive rice growth stages. Grain yield was calculated at 14% moisture content, while remaining plant parts were oven dried and weighed individually to determine dry biomass. The N concentration (%) and ¹⁵N enrichment in the different plant parts were measured after the samples were ground to powder. Plant samples were digested with H₂SO₄-H₂O₂. The Kjeldahl method was applied for the determination of N concentration in

Fig. 1 Schematic diagram of soil column used in experiment

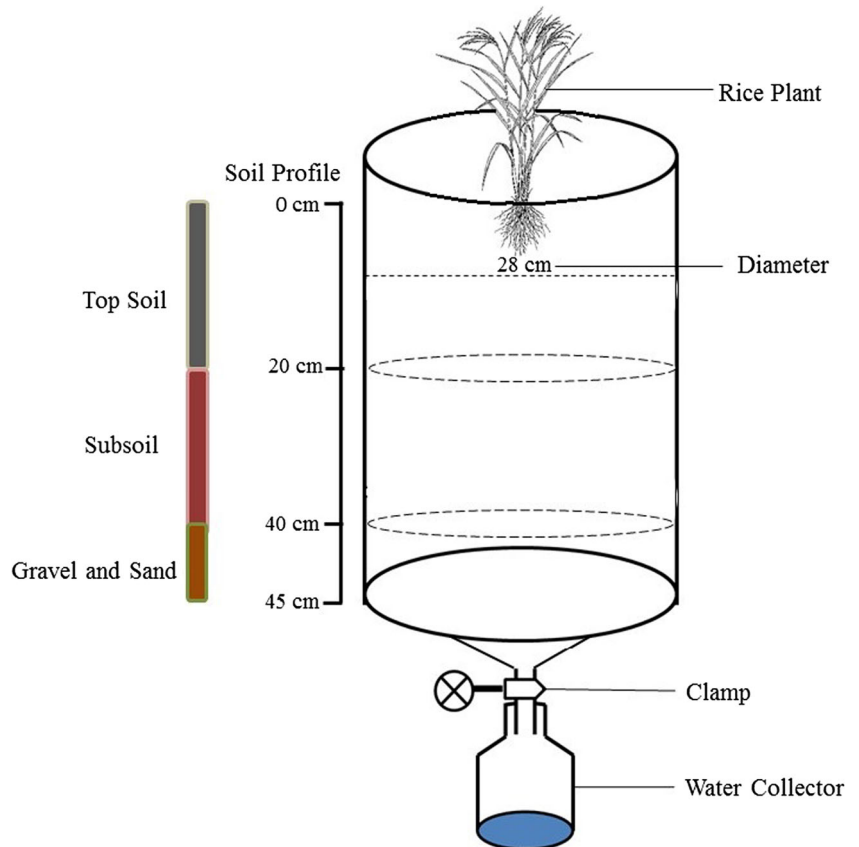


Table 2 Standards of two kinds of water application from transplanting to maturity

Growth stages	CI		TSM DI	
	Lower limit depth	Upper limit depth	Lower limit depth	Upper limit depth
After transplant	5 mm	40 mm	5 mm	40 mm
Early tillering	20 mm	30 mm	5 mm	30 mm
Late tillering	Soil was freely dried till small cracks			
Panicle initiation	20 mm	30 mm	5 mm	15 mm
Flowering	20 mm	30 mm	5 mm	15 mm
Ripening period	–	–	–	–

CI conventional irrigation, TSM DI “thin-shallow-moist-dry” irrigation

plant samples. The isotope analyses were carried out using an Elemental analyzer (Elementar Vario PYRO cube, Elementar, Hanau, Germany) equipped with an Isoprime isotope-ratio mass spectrophotometer (IRMS) with the precision of 0.3%.

During the plant growth period, leachate was collected at 5-day intervals. A plastic container was placed below each column. The volume of percolation water was recorded regularly during the whole rice growth season. After each sampling, leachate was immediately transferred to a laboratory for concerned observation. The $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and T-N (total nitrogen) in leachate were determined by indophenol blue and $\text{K}_2\text{S}_2\text{O}_8$ oxidation methods, using an ultraviolet spectrophotometer (AOE instruments, A580).

Irrigation water productivity was calculated as the ratio of total grain yield and total water utilized (kg grain m^{-3} water). Percentage of ^{15}N abundance was transformed into percentage ^{15}N excess, by subtracting the natural abundance (0.3663 at.% N) from the percentage of the N abundance of the sample.

Table 3 Irrigational water input and irrigation water productivity in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSM DI) and different N inputs

Treatment	Irrigation applied ($\text{m}^3 \text{ column}^{-1}$)		Irrigation water productivity (kg m^{-3})
Irrigation management	N inputs		
CI	N_0	0.030d	0.63d
	N_1	0.037b	0.76c
	N_2	0.040a	0.99b
TSM DI	N_0	0.026e	0.75c
	N_1	0.030d	0.99b
	N_2	0.033c	1.23a
Significance			
Irrigation management (I)		**	**
N inputs (N)		**	**
I × N interaction		ns	ns

Means followed by the same letter in each column are not significantly different at $P < 0.05$ (LSD test). $\text{N}_0 = 0 \text{ kg N ha}^{-1}$, $\text{N}_1 = 90 \text{ kg N ha}^{-1}$, $\text{N}_2 = 180 \text{ kg N ha}^{-1}$

ns not significant at $P > 0.05$

*Significant at $P < 0.05$

**Significant at $P < 0.01$

Nitrogen derived from fertilizer (%Ndff)

$$\text{N uptake (g plant}^{-1}\text{)} = \text{DM Yield (g plant}^{-1}\text{)} \times \% \text{Total N}/100$$

$$\text{Fertilizer N Yield (g plant}^{-1}\text{)} = \text{N Yield (g plant}^{-1}\text{)} \times \% \text{Ndff}/100$$

$$\% \text{NUE} = \text{Fertilizer N Yield}/\text{Rate of N application} \times 100$$

$$\text{Fertilizer N}_{\text{loss}} = \text{Fertilizer N}_{\text{input}} - \text{Fertilizer N}_{\text{uptake}} - \text{Fertilizer N}_{\text{residual}}$$

where Ndff is nitrogen derived from fertilizer, N is nitrogen, NUE is nitrogen use efficiency, DM is the dry matter

These calculations were according to the International Atomic Energy Agency (IAEA 2001).

Statistical analysis

Data were analyzed using a two-factor ANOVA (Statistix 8.1, Analytical Software, Tallahassee FL, USA), while the levels of significance are indicated by * $P < 0.05$ and ** $P < 0.01$ according to least significant difference (LSD) test.

Results

Irrigation volume and water productivity

Average water levels of thin-shallow-moist-dry irrigation (TSMDI) and conventional irrigation (CI) methods are presented in Table 2. The total amount of irrigation water during the whole growing season was 267.134 L in TSMDI and 323.770 L in CI. The amount of irrigation water for TSMDI was significantly reduced by 17.49% as compared to that for CI practice (Table 3).

Irrigation and nitrogen application had significant effects on water productivity. The irrigation water productivity varied between 0.63 and 1.23 kg m⁻³. The WP₁ in N₀ (0 kg N ha⁻¹) was lower compared to N₁ (90 kg N ha⁻¹) or N₂ (180 kg N ha⁻¹). The TSMDI practice recorded significantly higher irrigation water productivity at the same N rate. The WP₁ improvement of TSMDI was 0.16, 23.23, and 19.51% compared with CI at N₀, N₁, and N₂, respectively, and clearly indicated the superiority of TSMDI method due to a large decrement in water consumption (Table 3). As illustrated in Table 3, no significant water by nitrogen interaction was observed on applied irrigational water and water productivity.

Dry biomass and grain yield

The most important morphological difference between plants grown under CI and TSMDI was observed for their root growth, as depicted in Table 4a, b, c. The root dry biomass ranged from 1.586 to 2.436, 2.513 to 5.860, and 1.286 to 3.753 g plant⁻¹ at tillering, booting, and post-harvest stages, respectively. The results divulge that the root growth was less inhibited in the TSMDI method as compared with the growth of other plant parts. The difference in root dry biomass between CI and TSMDI treatments was statistically significant, which was attributed to moist dry phases that provide better aeration for root development (Table 4a, b, c). In both irrigation regimes, root dry biomass at three growth stages showed significant differences among N levels. At 180 kg N ha⁻¹ (local farmer's N application rate), root biomass was 3.69, 13.08, and 9.85% higher in TSMDI than in CI at tillering, booting, and post-harvest stages of rice, respectively (Table 4a, b, c).

The straw dry biomass ranged between 4.123 and 9.446, 11.110 and 19.667, and 7.470 and 16.833 g plant⁻¹ at tillering, booting, and post-harvest stages, respectively. During the whole growing season, the straw dry biomass was significantly higher in CI than TSMDI, except at tillering stage. However, under both water treatments, significant difference was noted for straw dry biomass (g plant⁻¹) with incremental rates of N at three stages (Table 4a, b, c). The leaf dry biomass ranged between 1.881 and 4.292, 2.920 and 5.196, and 2.240 and 4.896 g plant⁻¹ at tillering, booting, and post-harvest

stages, respectively. During the whole growth period, the leaf dry biomass was unaffected by irrigation management regimes, except at post-harvest, while it was considerably increased by the increment of N inputs. It was observed that root, straw, and leaf dry biomass were higher at the booting stage for both irrigation practices (Table 4a, b, c).

Grain yield ranged from 19.080 to 40.883 g plant⁻¹ under the influence of different irrigation methods and N levels (Table 4c). Compared with no N fertilizer treatment, application of 90 and 180 kg N ha⁻¹ increased grain yield by 33.31 and 52.52% under CI, and by 32.46 and 51.68% under TSMDI treatment, respectively. In general, response to incremental rates of N was more pronounced in TSMDI conditions than CI (Table 4c). The final biomass ranged from 7.643 to 16.087, 16.650 to 29.263, and 30.903 to 65.303 g plant⁻¹ at tillering, booting, and post-harvest stages, respectively. At three successive characteristics stages, the total biomass (g plant⁻¹) was comparatively higher in CI than of TSMDI, however, observed non-significant. During the whole growing season, the N inputs significantly influenced dry biomass of rice grown under both irrigation methods. The N application rate of 180 kg ha⁻¹ produced maximum dry biomass at physiological maturity and was significantly superior to lower N rates. However, no significant water by nitrogen interaction on the root, straw, leaf, grain, and total biomass at three successive characteristics stages of rice was observed, as depicted in Table 4a, b, c.

Nitrogen uptake and nitrogen use efficiency

Efficient utilization of applied N by the rice plant is one of the important factors determining the growth and yield of the crop. In the present study, the effect of irrigation methods and fertilizer N inputs was investigated by using ¹⁵N tracer on absorption, distribution, and utilization of the N by rice plants at successive characteristic stages so as to provide convincing information to ensure better crop yields and protect the environment. The root N uptake at three successive characteristic stages of development was significantly different under irrigation methods, as well as at different N levels (Table 5a, b, c). The TSMDI reflected higher root N uptake and might be due to better root system in TSMDI, which helped the plants to uptake more N compared with that in CI. Nitrogen fertilization treatments appreciably affected the concentration and uptake of N by plants in CI and TSMDI treatments. The root N uptake ranged between 0.0115 and 0.0241, 0.0135 and 0.0426, and 0.0065 and 0.0229 g plant⁻¹ at tillering, booting, and post-harvest stages, respectively (Table 5a, b, c).

The straw N uptake ranged between 0.0275 and 0.0866, 0.0685 and 0.1652, and 0.0313 and 0.1091 g plant⁻¹ at tillering, booting, and post-harvest stages, respectively. The straw N uptake was significantly different among different N levels,

Table 4 Dry biomass of different parts of rice and grain yield in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs at successive characteristic stages i.e. (a) tillering, (b) booting, and (c) post-harvest

Treatment		Root dry biomass (g plant ⁻¹)	Straw dry biomass (g plant ⁻¹)	Leaf dry biomass (g plant ⁻¹)	Grain yield (g plant ⁻¹)	Total biomass (g plant ⁻¹)
Irrigation management	N inputs					
a						
CI	N ₀	1.586d	4.150c	1.910c		7.647c
	N ₁	1.993c	7.310b	3.433b		12.740b
	N ₂	2.346b	9.446a	4.292a		16.087a
TSMDI	N ₀	1.640d	4.123c	1.881c		7.643c
	N ₁	2.056c	7.663b	3.441b		13.160b
	N ₂	2.436a	9.170a	4.244a		15.853a
Significance						
Irrigation management (I)		**	ns	ns		ns
N inputs (N)		**	**	**		**
I × N interaction		ns	ns	ns		ns
b						
CI	N ₀	2.513e	12.123c	3.076c		17.713c
	N ₁	3.570d	15.780b	4.083b		23.433b
	N ₂	5.093b	19.667a	5.196a		29.957a
TSMDI	N ₀	2.620e	11.110c	2.920c		16.650c
	N ₁	3.940c	14.913b	3.953b		22.807b
	N ₂	5.860a	18.473a	4.930a		29.263a
Significance						
Irrigation management (I)		**	*	ns		ns
N inputs (N)		**	**	**		**
I × N interaction		ns	ns	ns		ns
c						
CI	N ₀	1.286c	8.450e	2.283d	19.080c	31.100c
	N ₁	2.066b	13.297c	3.926bc	28.614b	47.903b
	N ₂	3.383a	16.833a	4.896a	40.190a	65.303a
TSMDI	N ₀	1.440c	7.470f	2.240d	19.753c	30.903c
	N ₁	2.416b	12.107d	3.166c	29.247b	46.937b
	N ₂	3.753a	15.690b	4.343ab	40.883a	64.670a
Significance						
Irrigation management (I)		*	**	*	ns	ns
N inputs (N)		**	**	**	**	**
I × N interaction		ns	ns	ns	ns	ns

Means followed by the same letter in each column are not significantly different at $P < 0.05$ (LSD test). N₀ = 0 kg N ha⁻¹, N₁ = 90 kg N ha⁻¹, N₂ = 180 kg N ha⁻¹

ns not significant at $P > 0.05$

*Significant at $P < 0.05$

**Significant at $P < 0.01$

while no significant difference was celebrated between two irrigation methods except at post-harvest, which might be due to straw biomass difference (Tables 4c and 5a, b, c). The N uptake for leaf ranged between 0.0364 and 0.1087, 0.0480 and 0.0991, and 0.0130 to 0.0367 g plant⁻¹ at tillering, booting, and post-harvest stages. The leaf N uptake was significantly different at all stages with N rates, while no

significant difference was observed between two irrigation methods (Table 5a, b, c).

At post-harvest, the grain N uptake ranged between 0.1744 and 0.4918 g plant⁻¹. Response to applied N for root and grain N uptakes was more conspicuous in TSMDI compared to CI, indicating that TSMDI increases the grains N accumulation (Table 5c). The total plant N uptake ranged between 0.0754

Table 5 Nitrogen uptake by different parts of rice in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs at successive characteristic stages i.e. (a) tillering, (b) booting, and (c) post-harvest

Treatment		Root N uptake (g plant ⁻¹)	Straw N uptake (g plant ⁻¹)	Leaf N uptake (g plant ⁻¹)	Grain N uptake (g plant ⁻¹)	Total N uptake (g plant ⁻¹)
Irrigation management	N inputs					
a						
CI	N ₀	0.0115d	0.0275c	0.0364c		0.0754c
	N ₁	0.0166c	0.0556b	0.0725b		0.1448b
	N ₂	0.0224b	0.0866a	0.1087a		0.2177a
TSMDI	N ₀	0.0119d	0.0276c	0.0373c		0.0769c
	N ₁	0.0175c	0.0600b	0.0742b		0.1517b
	N ₂	0.0241a	0.0820a	0.1080a		0.2140a
Significance						
Irrigation management (I)		*	ns	ns		ns
N inputs (N)		**	**	**		**
I × N interaction		ns	ns	ns		ns
b						
CI	N ₀	0.0135e	0.0735c	0.0494c		0.1365c
	N ₁	0.0223d	0.1136b	0.0688b		0.2046b
	N ₂	0.0361b	0.1652a	0.0991a		0.3004a
TSMDI	N ₀	0.0149e	0.0685c	0.0480c		0.1313c
	N ₁	0.0258c	0.1089b	0.0692b		0.2039b
	N ₂	0.0426a	0.1589a	0.0976a		0.2991a
Significance						
Irrigation management (I)		**	ns	ns		ns
N inputs (N)		**	**	**		**
I × N interaction		ns	ns	ns		ns
c						
CI	N ₀	0.0065c	0.0346e	0.0130c	0.1744c	0.2288c
	N ₁	0.0118b	0.0680c	0.0251b	0.2966b	0.4015b
	N ₂	0.0205a	0.1091a	0.0367a	0.4705a	0.6369a
TSMDI	N ₀	0.0075c	0.0313f	0.0133c	0.1871c	0.2391c
	N ₁	0.0143b	0.0633d	0.0206b	0.3140b	0.4121b
	N ₂	0.0229a	0.1022b	0.0335a	0.4918a	0.6504a
Significance						
Irrigation management (I)		*	**	ns	ns	ns
N inputs (N)		**	**	**	**	**
I × N interaction		ns	ns	ns	ns	ns

Means followed by the same letter in each column are not significantly different at $P < 0.05$ (LSD test). N₀ = 0 kg N ha⁻¹, N₁ = 90 kg N ha⁻¹, N₂ = 180 kg N ha⁻¹

ns not significant at $P > 0.05$

*Significant at $P < 0.05$

**Significant at $P < 0.01$

and 0.2177, 0.1313 and 0.3004, and 0.2288 and 0.6504 g plant⁻¹ at tillering, booting, and post-harvest stages. The total plant N uptake was increased with the increase in N input; however, both irrigation methods recorded statistically similar total plant N uptake during the whole growing season (Table 5a, b, c). Nevertheless, no significant water by nitrogen interaction was observed on the root, straw, leaf, grain, and

total N uptake at three successive characteristic stages of rice, as described in Table 5a, b, c.

The nitrogen derived from fertilizer (Ndff (%)) parameter provides a sensitive criterion by which to assess specific irrigation and fertilizer practices. In our study, at tillering stage, the Ndff (%) ranged from 28.55 to 33.62, 37.25 to 42.66, and 41.16 to 55.11 for root, straw, and leaf, respectively. At booting

stage, the Ndff (%) ranged from 24.50 to 30.60, 30.06 to 38.63, and 34.09 to 42.02 for root, straw, and leaf, respectively. While at the post-harvest, the Ndff (%) ranged from 16.97 to 20.49, 23.56 to 32.67, 25.71 to 34.56, and 27.89 to 36.57 for root, straw, leaf, and grain, respectively (Table 6a, b, c). The Ndff (%) was comparatively higher in TSMDI method than CI but was only statistically significant for root at the booting stage while, for straw and grain at post-harvest. At the tillering and booting stages, the N uptake was the highest in the leaves, while at the post-harvest, the highest N uptake was noticed in the grains, indicating the translocation of the absorbed N into the growing parts of the plant. The Ndff (%) revealed that N (%) per plant was higher under TSMDI compared to CI, but varied N uptake might be due to biomass difference (Tables 4,

5, and 6). The results indicated that across the whole growth period, the rice plant accumulated the highest amount of nitrogen from the tillering to booting stages. However, no significant water by nitrogen interaction was noted on the root, straw, leaf, and grain Ndff (%) at three successive characteristic stages of rice, as presented in Table 6a, b, c.

The fertilizer nitrogen yield (FNY) by root, straw, leaf, and grain plant⁻¹ at tillering, booting, and post-harvest stages were used in the calculation of nitrogen use efficiency (NUE). The NUE was decreased with the increment of N inputs. The NUE at the same levels of N was comparatively higher for TSMDI than CI. The root, straw, leaf, grain, and total NUE ranged from 1.96 to 2.59, 11.67 to 13.36, 9.96 to 11.19, 14.31 to 17.83, and 37.91 to 44.98%, respectively (Table 7). The

Table 6 Nitrogen derived from fertilizer (Ndff (%)) by different parts of rice in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs at successive characteristic stages i.e. (a) tillering, (b) booting, and (c) post-harvest

Treatment		Root Ndff (%)	Straw Ndff (%)	Leaf Ndff (%)	Grain Ndff (%)
Irrigation management	N inputs				
a					
CI	N ₁	28.55a	37.25b	41.16b	
	N ₂	32.16ab	43.80a	55.11a	
TSMDI	N ₁	29.52ab	38.43b	43.15b	
	N ₂	33.62a	42.66a	54.83a	
Significance					
Irrigation management (I)		ns	ns	ns	
N inputs (N)		*	**	**	
I × N interaction		ns	ns	ns	
b					
CI	N ₁	24.50b	30.06a	34.09b	
	N ₂	28.68a	36.51a	38.91ab	
TSMDI	N ₁	26.03b	32.25a	35.10b	
	N ₂	30.60a	38.63a	42.02a	
Significance					
Irrigation management (I)		*	ns	ns	
N inputs (N)		**	ns	*	
I × N interaction		ns	ns	ns	
c					
CI	N ₁	16.97b	23.56c	25.71b	27.89c
	N ₂	20.19a	28.41b	32.44a	33.70b
TSMDI	N ₁	17.40b	25.01c	27.93b	31.48b
	N ₂	20.49a	32.67a	34.56a	36.57a
Significance					
Irrigation management (I)		ns	*	ns	**
N inputs (N)		**	**	**	**
I × N interaction		ns	ns	ns	ns

Means followed by the same letter in each column are not significantly different at $P < 0.05$ (LSD test). N₁ = 90 kg N ha⁻¹, N₂ = 180 kg N ha⁻¹

ns not significant at $P > 0.05$

*Significant at $P < 0.05$

**Significant at $P < 0.01$

NUE under both irrigation methods was statistically similar to straw and leaf, while TSMDI recorded significantly higher NUE for root and grain compared with CI. Both irrigation methods and nitrogen levels recorded statistically significant total NUE. The improvement of total NUE in TSMDI at 90 kg N ha⁻¹ (moderate level of N application) and 180 kg N ha⁻¹ (local farmer’s N application rate) was 9.49 and 6.16% than in CI, respectively. It noted no significant water by nitrogen interaction on root, straw, leaf, grain, and total NUE (Table 7).

Water percolation

The total percolated water under TSMDI and CI in nine columns was 80.889 and 99.413 L, respectively. So, TSMDI reduced the percolation losses by 18.63% compared to CI (Fig. 2). The water percolation losses with both irrigation practices were almost the same until tillering stage, but gradually decreased afterward throughout the crop season for TSMDI. However, percolation losses were increased at booting stage as compared to other stages because mid-season freely soil drying helped in the formation of cracks. Considerable water leakage was observed from CI as the pond water continuously existed on the soil surface during the rice growth season.

Nitrogen concentration in percolated water

Nitrogen leaching is a physical process by which fertilizer N moves below the rooting zone with water that infiltrates through the soil. In the present work, fertilizer N inputs altered the NH₄⁺-N and T-N concentrations. The average NH₄⁺-N, NO₃⁻-N, and T-N concentrations in the percolated water with different irrigation and N management are given in Fig. 3. After top dressing of N fertilizer in both irrigation methods, the NH₄⁺-N and T-N concentrations in percolated water were

increased. Concentrations of NH₄⁺-N in percolated water were more eminent than those of NO₃⁻-N, caused by the application of ammonia (urea). The TSMDI recorded higher NO₃⁻-N concentrations while lowering the NH₄⁺-N and T-N in percolated water during the rice growth stage, compared with CI practice (Fig. 3a–c).

Ammonical concentration

The NH₄⁺-N concentrations varied with rice growth stages; however, peak values were observed at 10, 30, and 55 days after transplanting (DAT). Under both irrigation methods, the NH₄⁺-N mean values were 2.1, 2.8, and 4.2 mg L⁻¹ with N₀, N₁, and N₂ treatment at DAT = 10 (rice regreen stage), respectively. At 30 DAT (tillering stage), the NH₄⁺-N concentrations for N₀, N₁, and N₂ treatments were 1.4, 2.9, and 4.5 mg L⁻¹ under CI, and 1.4, 2.8, and 4.2 mg L⁻¹ under TSMDI method, respectively. Therefore, at DAT = 55 (booting stage), the NH₄⁺-N concentrations for N₀, N₁, and N₂ treatments were 1.1, 1.88, and 3.5 mg L⁻¹ under CI, and 0.87, 1.68, and 3.2 mg L⁻¹ under TSMDI method, respectively (Fig. 3a). The average leaching of NH₄⁺-N during the whole experiment was 9.96% lower in TSMDI compared with CI practices. During the whole growing season, the average leaching of NH₄⁺-N was 1.02, 1.84, and 2.67 mg L⁻¹ for CI and 0.90, 1.61, and 2.47 mg L⁻¹ for TSMDI at N₀, N₁, and N₂ inputs, respectively. Aerobic conditioning in TSMDI promoted the nitrification, which brought down the concentration of NH₄⁺-N in leachate compared to CI (Fig. 3a).

Nitrate concentration

On the other hand, irrigation management was the predominant factor of NO₃⁻-N concentrations in leachate rather than

Table 7 Nitrogen use efficiency (NUE) % in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs

Treatment		Root NUE (%)	Straw NUE (%)	Leaf NUE (%)	Grain NUE (%)	Total NUE (%)
Irrigation management	N inputs					
CI	N ₁	2.20b	12.78a	10.78a	14.93bc	40.71b
	N ₂	1.96c	11.67a	9.96a	14.31c	37.91b
TSMDI	N ₁	2.59a	13.36a	11.19a	17.83a	44.98a
	N ₂	2.33b	11.72a	10.09a	16.25ab	40.40b
Significance						
Irrigation management (I)		**	ns	ns	**	*
N inputs (N)		**	*	ns	ns	*
I × N interaction		ns	ns	ns	ns	ns

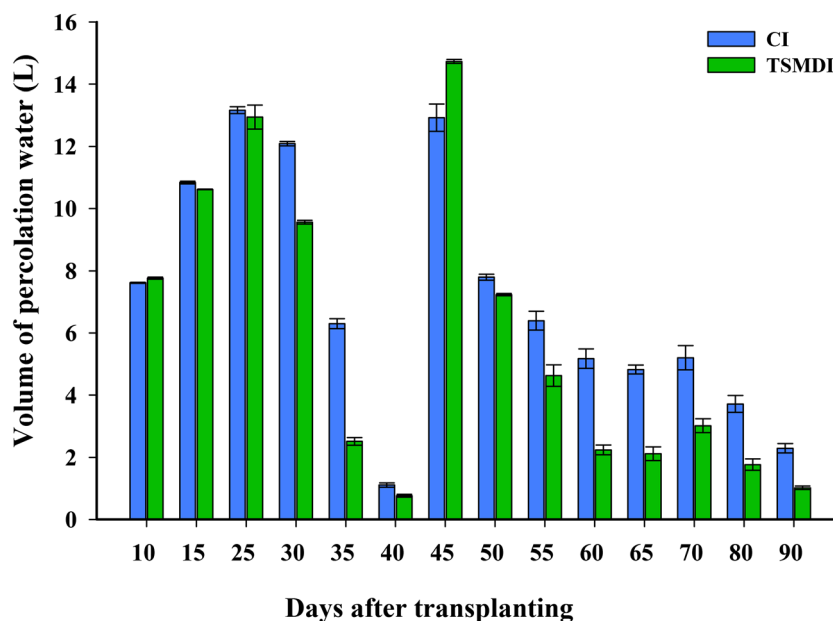
Means followed by the same letter in each column are not significantly different at P < 0.05 (LSD test). N₁ = 90 kg N ha⁻¹, N₂ = 180 kg N ha⁻¹

ns not significant at P > 0.05

*Significant at P < 0.05

**Significant at P < 0.01

Fig. 2 Water percolation in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs



by N inputs. The highest mean values of NO_3^- -N were observed at 45 DAT. The NO_3^- -N leaching for N_0 , N_1 , and N_2 treatment was 0.06, 0.12, and 0.16 mg L^{-1} under CI, and 0.07, 0.17, and 0.23 mg L^{-1} under TSMDI, respectively, at 45 DAT and were much lower than NH_4^+ -N concentration (Fig. 3b). The average concentration of NO_3^- -N in percolated water in the whole rice season under TSMDI was 26.41% higher than that under CI method. The average NO_3^- -N concentrations at N_0 , N_1 , and N_2 treatment were 0.014, 0.047, and 0.061 mg L^{-1} under TSMDI, and 0.015, 0.064, and 0.086 mg L^{-1} under CI methods, respectively. In percolation water, the NO_3^- -N concentrations were higher under TSMDI than CI at the same N level. The aerobic environment during wetting and drying phases of TSMDI favored the nitrification and weakened the denitrification (Fig. 3b).

Total N concentration

The total nitrogen (T-N) concentrations in percolated water varied similarly as NH_4^+ -N for different irrigation and N inputs and were chiefly regarded by N fertilization. After urea application, the T-N concentrations increased immediately in both irrigation methods. The average T-N concentration in leachate was 1.93 and 1.80 mg L^{-1} for TSMDI and CI, respectively. The average T-N concentration was reduced by 7.13% under TSMDI compared to CI. However, at N_0 , N_1 , and N_2 , it was 0.94, 1.75, and 2.69 mg L^{-1} under TSMDI, and 1.05, 1.93, and 2.81 mg L^{-1} under CI method, respectively (Fig. 3c). The contribution of applied N fertilizer in N leaching increased with the increment N rate used under both irrigation systems.

Fertilizer nitrogen balance

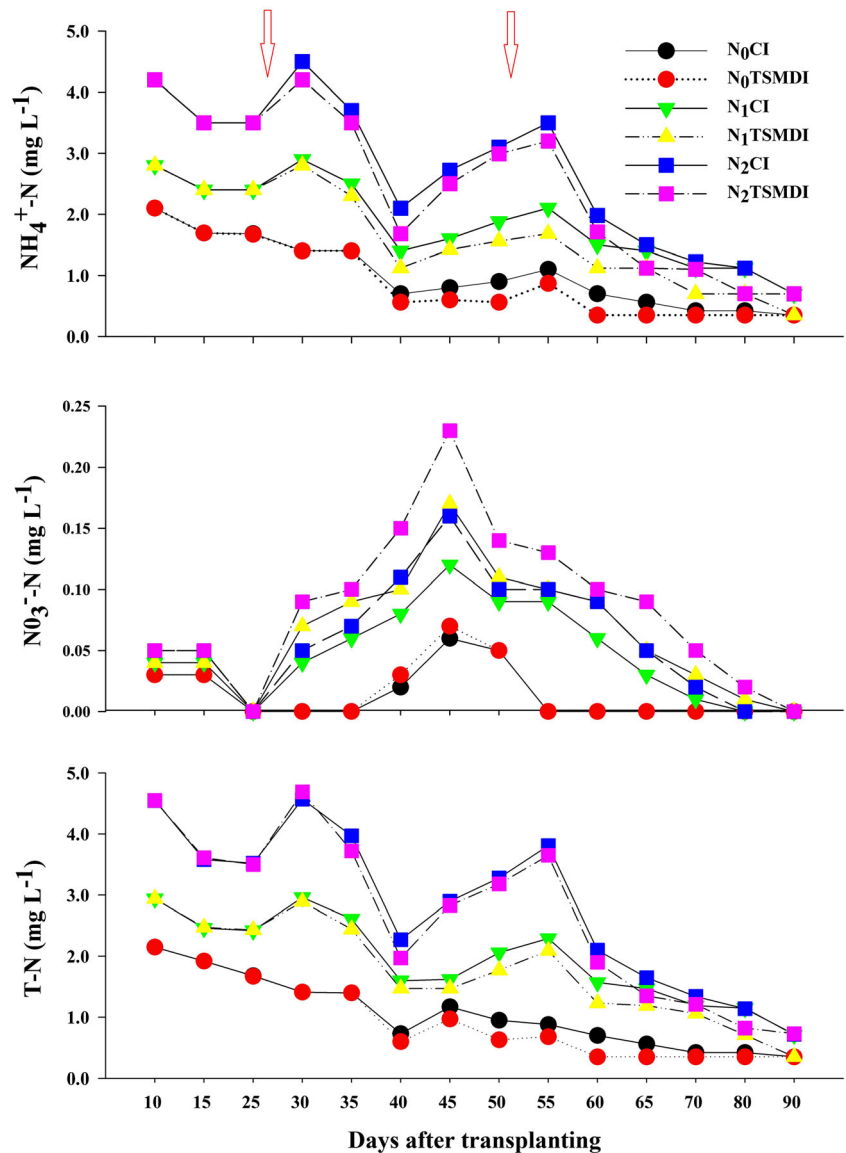
It is fair to accept that only the portion of N absorbed into the plant can be utilized; the rest will be washed off into the water system or lost in the atmosphere, both causing environmental pollution. In the present study, the fertilizer $\text{N}_{\text{residual}}$, fertilizer N_{uptake} , and fertilizer N_{loss} ranged between 0.228 and 0.455, 0.225 and 0.448, and 0.076 and 0.253 (g column^{-1}), respectively. Both irrigation methods were statistically similar regarding these attributes except for fertilizer N_{uptake} (g column^{-1}). However, increase in N inputs enhanced the fertilizer $\text{N}_{\text{residual}}$, fertilizer N_{uptake} , and fertilizer N_{loss} (g column^{-1}), as shown in Table 8.

The fertilizer $\text{N}_{\text{residual}}/\text{fertilizer N}_{\text{inputs}}$, fertilizer $\text{N}_{\text{uptake}}/\text{fertilizer N}_{\text{inputs}}$, and fertilizer $\text{N}_{\text{loss}}/\text{fertilizer N}_{\text{inputs}}$ ranged between 39.18 and 42.84, 37.91 and 44.97, and 13.73 and 22.90%, respectively. The fertilizer N inputs and irrigation methods had a non-significant effect on $\text{N}_{\text{residual}}/\text{fertilizer N}_{\text{inputs}}$ (%), while fertilizer $\text{N}_{\text{loss}}/\text{fertilizer N}_{\text{inputs}}$ (%) was significantly affected by N inputs. Contrarily, fertilizer $\text{N}_{\text{uptake}}/\text{fertilizer N}_{\text{inputs}}$ (%) was significantly affected by irrigation methods and fertilizer N inputs. However, no statistically significant water by nitrogen interaction was observed on selected parameters in Table 8.

Discussion

It is even moot, whether intermittent irrigation practice during rice cultivation could accomplish the dual goal of increasing grain production and saving water. The urgent requirement for sustainable agriculture is the optimal use of water and nutrients (Yao et al. 2012). In

Fig. 3 Nitrogen leaching in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs. $N_0 = 0 \text{ kg N ha}^{-1}$, $N_1 = 90 \text{ kg N ha}^{-1}$, $N_2 = 180 \text{ kg N ha}^{-1}$ (arrows show N fertilizer top dressing)



this study, the consequence of irrigation management and traditional N inputs of the Hubei Province on water productivity, N dynamics, and grain yield were investigated. The results revealed that the thin-shallow-moist-dry (TSMDI) appreciably decreased irrigation water input, N-leaching, while increased water productivity without jeopardizing grain yield.

Water-saving mechanism by TSMDI

The causes of high water productivity by using TSMDI are that the reduced irrigation water requirement, and improved rice grain yield (Tables 3 and 4c). However, the reasons for the reduction of the irrigation water requirements are large decrement of the percolation and evapotranspiration. The reduction of percolation results from two ways. (1) The duration of no water depth and unsaturated condition in paddy soil is longer

under TSMDI than under CI. (2) The depth of water depth is shallower under TSMDI than that under CI (Table 2). The data can also prove this situation (Fig. 2). Under TSMDI, most of the time the average soil moisture content in the root zone (0–40 cm) is in 80–90% of field capacity. It leads to the average soil moisture content in 0–5 cm of the surface layer below 50% of field capacity (Mao 2000; Sujono et al. 2011). Under this condition, the rice growth is not affected, but the evaporation from paddy soil can be reduced (Cabangon et al. 2004). So, instead of keeping the flooded condition, the standing water depth can be decreased by adopting water-saving techniques, especially in the scenario of water crises (Bouman 2001). The wetting and drying irrigation method conformed to the physiological water demand of paddy rice by rationally controlling water supply during rice’s key growth stages so that irrigation water could be cut down (Mao 2000; Cabangon et al. 2011; Yao et al. 2012).

Table 8 Fertilizer N balance in conventional irrigation (CI) and “thin-shallow-moist-dry” irrigation (TSMDI) and different N inputs

Treatment	Fertilizer N _{applied} (g column ⁻¹)	Fertilizer N _{residual} (g column ⁻¹)	Fertilizer N _{uptake} (g column ⁻¹)	Fertilizer N _{loss} (g column ⁻¹)	Fertilizer N _{residual} /fertilizer N _{inputs} (%)	Fertilizer N _{uptake} /fertilizer N _{inputs} (%)	Fertilizer N _{loss} /fertilizer N _{inputs} (%)
Irrigation management							
	N inputs						
CI	N ₁	0.554	0.237b	0.225b	0.091b	42.84a	40.70b
	N ₂	1.108	0.434a	0.420a	0.253a	39.18a	37.91b
TSMDI	N ₁	0.554	0.228b	0.249b	0.076b	41.28a	44.97a
	N ₂	1.108	0.455a	0.448a	0.205a	41.05a	40.40b
Significance							
Irrigation management (I)		ns	*	ns	ns	*	ns
N inputs (N)		**	**	**	ns	ns	*
I × N interaction		ns	ns	ns	ns	ns	ns

Means followed by the same letter in each column are not significantly different at $P < 0.05$ (LSD test). N₁ = 90 kg N ha⁻¹, N₂ = 180 kg N ha⁻¹

ns not significant at $P > 0.05$

*Significant at $P < 0.05$

**Significant at $P < 0.01$

Crop performance influenced by TSMDI

Rice root systems play an important role in the acquisition of nutrients and water. Table 4a, b, c divulged that the difference in root dry biomass between CI and TSMDI treatments was statistically significant, which was attributed to moist dry phases that provide better aeration for root development. The rice roots can grow well under oxidized paddy soil, even under moderate water stress (Siopongco et al. 2005). The main zone of rice roots under TSMDI is deeper than that under CI. During the root sampling, it was found that the roots distributed as a net within the top surface under CI but branches well under TSMDI. The moist dry irrigation succession during rice cultivation tends to result in a rather dramatic change in the soil physical environment including the transition between aerobic and anaerobic. Besides, with wetting and drying cycles, TSMDI strengthens the air exchange between soil and the atmosphere (Tan et al. 2013). Therefore, sufficient oxygen is supplied to the root system to accelerate soil organic matter mineralization and to inhibit soil N mobilization, all of which should increase soil fertility and produce more essential plant-available nutrients to favor rice growth (Dong et al. 2012). Consistent with our results, Samejima et al. (2004) reported that root physiology and morphology are closely related to the growth of aerial parts of plant (Table 4a, b, c).

Plant biomass is an important growth parameter which represents the crop input utilization. During the whole growing season, the straw dry biomass was significantly higher in CI than TSMDI, except at tillering stage (Table 4a, b, c). It might be ascribable to the fact that the TSMDI practice suppresses the non-effective tillers (vegetative growth redundancy), and to promote effective tillers, which enhances the number of spikelet and 1000-grain weight, thus ultimately leads to higher grain yield (Mao 2000). However, under both water treatments, significant difference was noted for straw dry biomass (g plant⁻¹) with incremental rates of N at three stages, whereas irrigation methods did not influence significantly on total biomass at successive growth stages, which might be ascribable to the sufficient moisture contents in the root zone for plant activity (Table 4a, b, c). It might be suspected that CI and TSMDI methods have the similar evapotranspiration; this hypothesis is well evident, as both irrigation methods had a non-significant difference for grain yield and biomass, indicating that there exists a minor difference between irrigation methods for transpiration. In addition, under TSMDI method, the soil moisture content was kept about saturated. So, the evaporation from wet soil would not vary too much compared to CI (Table 4a, b, c; Cabangon et al. 2004).

In present work Table 4c divulge that, rice grain yield exhibited non-significant differences between irrigation methods; merely, it was slightly higher under TSMDI practice, as it reduced the vegetative growth redundancy (Wang et al. 2016). It might be ascribable to the fact that the moderate

moist dry irrigation technique during grain filling could increase the grain-filling rate of spikelets and increase grain weight (Yang and Zhang 2010). Our findings are in prop up with the observations of Zhao et al. (2011) that rice can be cultivated under water-saving methods in which conventional irrigation system is not indispensable to attain higher grain yield and dry biomass production (Table 4). In the present study, the fertilizer N inputs resulted in a substantial increase of grain yield over the treatment receiving no N. Previously, de Vries et al. (2010) reported that grain yield was triggered by N fertilizer application, not by irrigation (Table 4c).

¹⁵N uptake efficiency and N leaching in paddy soil

To mimic high input cropping systems in Southern China, the traditional application rate of the Hubei Province was investigated. Hence, we practiced a range of parameters, of which plant N uptake, NUE %, and N leaching are the most indicative, to describe N economy subsequently affected by water regimes. The aim of the ¹⁵N was to investigate the actual N uptake during three successive characteristic growth stages in different parts of the plant, and to facilitate the effective role of fertilizer in rice. The root N uptake at three successive characteristic stages of development was significantly different under irrigation methods, as well as at different N levels (Table 5a, b, c). Plant analysis showed that the nitrogen derived from fertilizer was comparatively higher under TSMDI during three successive characteristic stages of development, indicating higher N distribution among different parts of the rice plant, especially in grain (Table 6a, b, c). Tables 5c and 6c show that more N accumulation was noted in rice grain under TSMDI, which might be due to more N uptake by the root medium which predominantly translocates to the upper parts of the plant (Stoop et al. 2002; Horie et al. 2005; Lin et al. 2006). Another clarification is that continuous rice flooding significantly reduces oxygen supply to the root system which impairs nutrient uptake (Sahrawat 2000; Olaleye et al. 2001; Yang et al. 2004). So, the highest grain N uptake in rice was associated with maximum grain yield, as also reported by Fageria (2003).

To achieve high crop production, farmers use a lot of chemical N fertilizers every year. As a result, the efficiency of N utilization in crops is notoriously low (Rekhi and Meelu 1982). However, in the current study, the significantly higher root and grain NUE, is the evidence of efficient utilization of nitrogenous fertilizer influenced by TSMDI, as presented in Table 7. The improvement of total NUE in TSMDI at 90 kg N ha⁻¹ (moderate level of N application) and 180 kg N ha⁻¹ (local farmer's N application rate) was 9.49 and 6.16% than in CI, respectively. The significantly higher total NUE in TSMDI than CI in this study (Table 7) suggested that the consequent nitrification-denitrification process under mild-stress TSMDI was not severe enough to cause a greater loss of N compared with CI (Cabangon et al. 2011). Withal, the N that is not taken

up aside the rice crop is the potential cause of groundwater pollution through leaching (Thuy et al. 2008).

In the present study, the successful implementation of water-saving irrigation reduced N leaching losses comparatively than CI at the same N management, because of a substantial decrement in the volume of percolation water (Fig. 2) (Peng et al. 2015). The forms of nitrogen, i.e., NH₄⁺-N and NO₃⁻-N losses through leaching in paddy fields, are quite different in limited studies (Peng et al. 2011). Some reports have indicated that NO₃⁻-N is the important N loss pathway under conventional agricultural N management practices (Zhu and Chen 2002). Moreover, NO₃⁻-N is one of the most widespread groundwater pollutants, and drinking water with high NO₃⁻-N concentration may contribute to adverse health effects. Consequently, much attention has been focused on NO₃⁻-N leaching (Gehl et al. 2005) in paddy soils. In the present study, however, we noted that the NH₄⁺-N was the main form of total nitrogen in leachate during the plant growth period (Fig. 3a–c). The excess application of NH₄⁺-N-based fertilizers (urea) overloaded the soil adsorption capacity, which might have caused the NH₄⁺-N leaching (Qian and Cai 2007). The outcomes of the present study coincided with the findings of Xiong et al. (2010) who reported that NH₄⁺-N makes up to 92% of the total inorganic N in the leachate (Fig. 3).

Thus, the cause behind the reduction in NH₄⁺-N leaching losses in percolation water for TSMDI is that during CI, the paddy soil remains in a reduced environment and nitrification process was limited, while denitrification was intensive (Peng et al. 2011). On the other hand, moist-dry phases of TSMDI method encouraged the paddy soil oxygen content, which sped up the nitrification. This contributed to the largest concentration of NO₃⁻-N in the percolated water for TSMDI compared to CI under the same N managements (Peng et al. 2015). Our results confirmed that NH₄⁺-N movement in soil is greatly influenced by irrigation regimes and that the vast potential risk of NH₄⁺-N leaching deserves more attention.

Agronomists always have known that a substantial portion of the fertilizer N applied to soil is lost by a process other than plant uptake. Although they always have tried to identify practices that cut these losses. Regarding the fertilizer N balance in the present study, TSMDI method had higher fertilizer N_{uptake} and less fertilizer N_{loss} (g column⁻¹) compared to CI practice (Table 8), which might be due to extensive and well-established root system in TSMDI compared to CI that helped in the uptake of more N. The TSMDI reduced water input, which was primarily attributed to the reduction of seepage and percolation losses that ultimately minimized N-leaching (Table 3 and Figs. 2 and 3).

However, based on the study results, we conclude that TSMDI-N₂ was the most rational regime, over other treatment's combinations due to higher grain yield and water productivity (Tables 3 and 4c). To the contrary, TSMDI-N₁ appeared as the best combination of water and N application due to higher NUE and reduction in N-leaching loss (Table 7 and

Fig. 3). In crux, the data of the present study warrant further studies the subsequent effects of TSMDI along with optimal nitrogen management strategies for sustainable agricultural systems.

Conclusion

The foremost task in rice cultivation is to attain the higher food production and resource use efficiency. The present study evaluated the impacts of a controlled irrigation technique in rice production called thin-shallow-moist-dry irrigation (TSMDI). How can we reduce water application under TSMDI method without jeopardizing rice grain yield? Essentially, TSMDI method creates more satisfactory soil crop environment, as compared to the conventional rice cultivation with the continuous flooded field. In the present work, we demonstrated considerable changes in characteristics of TSMDI compared to CI method. Our results showed that TSMDI improved the root growth, which facilitated the uptake of water and nitrogen. The irrigation volume for TSMDI was 17.49% less compared with CI without jeopardizing grain yield. Isotopically labeled ^{15}N was supportive to examine the fate of applied N in different plant parts and estimating fertilizer NUE. The water leakage from TSMDI method was 18.63% lower than that from CI, which favored in the reduction of N leaching losses appreciably. The consequences of fertilizer N balance might be supportive for efficient resource utilization. The data of the present study warrant further investigations to better understand fertilizer N balance including greenhouse gas emission influenced by TSMDI in order to offer a convincing information to ensure better crop yields and protect the environment.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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