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Increasing Effective Use of Straw-Derived Nitrogen by Alternate Wetting/Drying Irrigation Combined with N Fertilization Addition in a Soil–Rice System

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Abstract: Straw-derived N (Straw-N) is an important organic N source, but its distribution in soil–rice systems regulated by water management and N fertilization is poorly understood. Therefore, a pot experiment using ^{15}N -labeled wheat residue was conducted with conventional flooded irrigation (CF) and alternate wetting/drying irrigation (AWD) both with and without N fertilization. Results showed that the whole-plant straw-N recovery rate and the soil residue rate were 9.2–11.9% and 33.5–43.1%, and 10.2–13.8% and 33.7–70.2% at panicle initiation stage (PI) and mature stage (MS), respectively. There was no interaction between water management and N fertilization. Compared to CF, AWD did not affect whole-plant straw-N absorption and significantly changed its distribution in various plant parts, such as increasing the straw-N accumulation in roots at PI and decreasing it at MS. N fertilization addition markedly promoted the transfer of straw-N to the plant but reduced the contribution rate of N uptake by the plant. Furthermore, AWD or N fertilization addition allowed more straw-N to remain in the soil, and a positive interaction effect on the straw-N loss mitigation was found. These results suggest that AWD combined with N fertilization addition is a great measure to improve the efficient utilization of straw-N and avoid the risk of environmental pollution in a soil–rice system.

Keywords: straw-derived nitrogen; distribution; water management; nitrogen fertilization; soil–rice system

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1. Introduction

Rice is a vital staple food, feeding over 50% of the global population [1]. China is the world's largest rice-producing country, accounting for 27.4% of global rice production [2], and thus China's rice cropping systems play an important role in satisfying global food demand. The rice–wheat system is the most popular cropping system in China, with an area of 13 million hectares and an average straw production of 4 t ha^{−1} [3,4]. Straw incorporation is widely regarded as a great management practice to improve soil fertility and increase rice production [4–6], providing abundant straw-derived nitrogen (straw-N) to the soil and aiding in rice growth [7–10]. The annual total amount of straw-N in China is 5.5×10^6 t for rice and 5.4×10^6 t for wheat [11]. Therefore, to enhance the efficient utilization of straw nutrients, it is necessary to better understand the distribution of straw-N and its contribution to a soil–rice system, especially in rice–wheat systems.

Water management and N fertilization are common agricultural measures that affect the N cycle in soil–rice systems [12–15]. Generally, water management dramatically changes the physical environment of the soil (e.g., soil O₂ condition and soil moisture) [16], regulating rice growth and altering soil microbial processes (e.g., mineralization, nitrification, and denitrification). Recently, a novel water-saving technique, alternate wetting and drying

irrigation (AWD), was reported [17,18]. This practice could improve soil aeration [16], reduce the abundance of toxic substances [19,20], and promote root activities and N uptake by rice [21–23], while simultaneously decreasing greenhouse gas emissions [21,24] and N loss from runoff and leaching [25,26]. Furthermore, straw decomposition or straw-N release depends on soil moisture [27–31], which may impact the transformation of released straw-N to the soil and rice plants. However, to the best of our knowledge, no experiment has so far systematically assessed the effect of AWD on straw-N allocation in soil–rice systems.

Incubation studies and field experiments have suggested that inorganic N addition accelerates the decomposition rate of low-quality straw (namely, high ratio of C to N (C/N), such as wheat straw) because it reduces C/N in the soil [32–35]. Pot and field experiments, using a ^{15}N tracer method, in dryland systems showed that N fertilization application enhances straw-N uptake by the plant but decreases the amount of straw-N in the soil due to the increased loss of straw-N [8,36]. However, unlike the dryland system, the paddy system has a unique irrigation mode and different dominant pathways of N loss (e.g., surface runoff, leaching, and ammonia volatilization) [37]. Therefore, the response of straw-N utilization and loss to N fertilization application in the irrigation rice system may differ, but the current research is unclear.

The interaction of water management and N fertilization on their effects on rice growth, N uptake, and N loss by gas emissions in rice–wheat systems has been gaining considerable attention [38–41], but there is a lack of systemic studies on the distribution of wheat straw-N. Therefore, in this study, a ^{15}N -labeled wheat straw method was used in a pot experiment under two water management regimes with or without N fertilization application. This study aimed to (1) trace straw-N transfer to rice plants in a rice–wheat system and (2) accurately assess the effect of water management, N fertilization, and their interaction on returned wheat straw-N distribution and its contribution to the soil–rice system.

2. Materials and Methods

2.1. Experiment Site

A pot experiment was conducted at the Danyang test base of Nanjing Agriculture University (NJAU) (Longitude $119^{\circ}10'$, Latitude $34^{\circ}36'$), Jiangsu Province, China. The test base was located in the Yangtze River's lower reaches of the rice–wheat rotation system area. The soil type was typical yellow loam soil. The soil main physicochemical properties were as follows: pH, 6.0; total organic carbon, 6.0 g kg^{-1} ; total N, 0.9 g kg^{-1} ; total K, 11.0 g kg^{-1} ; total P, 0.5 g kg^{-1} ; available N, 73.0 mg kg^{-1} ; available P, 13.6 mg kg^{-1} ; available K, 93.5 mg kg^{-1} .

2.2. Preparation of ^{15}N -Labeled Wheat Straw

To obtain ^{15}N -enriched wheat straw material, a ^{15}N pulse labeling experiment was conducted in the greenhouse in 2015. Briefly, wheat (Yangmai 20#) was sown in the artificial sandy land on 15 November 2015, applying ^{15}N -labeled urea (the abundance of ^{15}N isotope was 98%) at the early booting stage. The ^{15}N -labeled wheat was harvested into spikes and straw (including stems and leaves), and then dried at $40\text{ }^{\circ}\text{C}$ for 48 h. Then, the wheat straw was chopped into approximately 3–5 cm segments and stored in airtight jars. A small number of wheat straw samples were ground for analysis, using an isotope ratio mass spectrometer (IRMS) coupled with a Flash HT Plus elemental analyzer (Thermo Fisher Scientific, Bremen, Germany). ^{15}N -labeled wheat straw was 0.68% in total N, 41.7% in total C, and 46.9% in atom% ^{15}N values.

2.3. Experimental Design

This experiment was conducted using pot with a diameter of 35 cm and a height of 30 cm, and 15 kg of fine-grained soil (passed through a 5 mm sieve, 0–20 cm depth). ^{15}N -labeled wheat straw rate was 45 g pot^{-1} and was added into pots after through mixing

with soil on 15 June 2016. The treatment without wheat straw incorporation was assigned as the control. Rice seed (*Oryza saliva* subsp. *japonica*, conventional japonica cultivar) was sown on 30 May, transplanted on 22 June, and harvested on 30 October 2016. The planting density was three holes per pot and three seedlings per hole. This density was similar to the field transplanting density (a hole spacing of 13.3 cm $\times$ 30 cm with three seedlings per hole). Average temperature and photosynthetically active radiation were collected using automatic weather station (Watch Dog 2900Et, Spectrum, CA, USA) (Figure 1).

Figure 1. Meteorological parameters during the rice season.

Treatments included two water management regimes (CF: conventional flooded irrigation; AWD: alternate wetting/drying irrigation) and two N fertilization levels (N_0 : without N fertilizer; N_1 : with 300 kg N ha⁻¹), giving a total of four treatments with ten pots per treatment. In the CF treatment, each pot was continuously flooded with a 3–5 cm water level until one week before harvest, except for drainage mid-season. The AWD treatment method was based on Chu et al. [21]: pots were kept at a 2–3 cm water level during the first week after transplanting, the panicle initiation stage (PI). At other growth stages, pots were not irrigated until the soil moisture content was about 0.2–0.3 g g⁻¹ using a soil moisture meter (SMT-SWC-BX, Nanjing Smartsience Sensor Manufacturing Factory, Nanjing, China). Inorganic N fertilizer was used as basal fertilizer, tillering fertilizer, panicle-promoting fertilizer, and panicle-protecting fertilizer in the ratio of 3:3:2:2 (namely fertilizer rate was 0.6 g pot⁻¹, 0.6 g pot⁻¹, 0.4 g pot⁻¹, and 0.4 g pot⁻¹, respectively). All doses of K fertilizer (270 kg P₂O₅ ha⁻¹) and P fertilizer (180 kg P₂O₅ ha⁻¹) were applied on 15 June 2016.

2.4. Sampling and Analytical Measurements

Three pots with similar growth were selected in each treatment as three replicates. Plant samples in each pot (including root, stem and leaf, panicle and undecomposed wheat straw) were collected at PI and MS (day 48 and day 133 after straw incorporation) for further analysis. For collecting root and undecomposed ¹⁵N-labeled wheat straw sampling, a whole pot of the soil (only containing rice roots and undecomposed ¹⁵N-labeled wheat straw) was poured into a 0.25 cm mesh bag and was washed with water cannon. Next, we separated the remaining residues (including large particles of soil, rice roots, and undecomposed wheat straw) using some appearance characteristics (e.g., length and shape). All plant samples were oven-dried at 75 °C to a constant weight to determine dry matter accumulation. Ground plant samples were passed through a 0.15 mm sieve to determine total N contents and ¹⁵N isotope abundance values, using IRMS coupled to a Flash HT Plus elemental analyzer (Thermo Fisher Scientific, Bremen, Germany).

Three separate samples from each pot using a soil extractor (a diameter of 1 cm) were collected and mixed before collecting plant samples. Soil samples were air-dried in a room. After all visible roots and straw were removed, the soil was ground and passed through a 0.15 mm sieve to measure total N content and ^{15}N isotope abundance values using IRMS coupled to a Flash HT Plus elemental analyzer (Thermo Fisher Scientific, Bremen, Germany).

2.5. Calculations and Statistical Analysis

The percentage N derived from straw residues ($Ndfs$, %) was calculated according to the following equation [8]:

$$Ndfs_{sample}(\%) = (Atom_{sample} - Atom_{control}) / (Atom_{straw} - Atom_{control}) \times 100 \quad (1)$$

where $Atom_{sample}$ is the atom% ^{15}N values of the plant samples (leaves, stems, panicles, root and undecomposed straw) and soil samples. $Atom_{straw}$ is the atom% ^{15}N values of initially added ^{15}N -labeled wheat straw. $Atom_{control}$ is the atom% ^{15}N values of the corresponding plant or soil samples in the treatment without wheat straw.

The amount of straw-N taken up by various rice parts (including root, stem-leaf and panicle) was calculated as follows:

$$\text{Straw} - \text{N accumulation (mg pot}^{-1}) = \text{Dry matter weight (g pot}^{-1}) \times N_{plant \text{ content}}(\%) \times Ndfs_{sample}(\%) \times 10^{-1} \quad (2)$$

The amount of straw-N residue in the soil was calculated as follows:

$$\text{Straw} - \text{N residue in soil (mg pot}^{-1}) = Ndfs_{soil}(\%) \times N_{soil}(\%) \times \text{Soil weight (kg pot}^{-1}) \times 10^{-1} \quad (3)$$

The straw-N contribution rate represented the proportion of the straw-N accumulation to the total N in plant or soil samples, and was calculated as follows:

$$\text{Straw} - \text{N contribution rate (\%)} = (2) \text{ or } (3) / TN_{plant \text{ or soil}}(\text{mg pot}^{-1}) \times 100 \quad (4)$$

where TN_{plant} is the total N absorption in the corresponding plant parts (mg pot^{-1}). TN_{soil} is the soil N sequestration (mg pot^{-1}).

The amount of straw-N loss (e.g., runoff and gas emission) in a soil-rice system was calculated, using straw-N balance as follows:

$$\begin{aligned} \text{Straw} - \text{N loss (mg pot}^{-1}) = & \text{Added Straw} - \text{N amount (mg pot}^{-1}) \\ & - \text{Total straw} - \text{N accumulation in plant and soil (mg pot}^{-1}) \\ & - \text{undecomposed straw} - \text{N amount (mg pot}^{-1}) \end{aligned} \quad (5)$$

The recovery rate of straw-N in the plant, the residual rate of straw-N in the soil, and the loss rate of straw-N were calculated as follows:

$$\text{Straw} - \text{N recovery rate (\%)} = \text{straw} - \text{N accumulation in plant (mg pot}^{-1}) / \text{added straw} - \text{N amount (mg pot}^{-1}) \times 100 \quad (6)$$

$$\text{Straw} - \text{N residual rate (\%)} = \text{straw} - \text{N residue in soil (mg pot}^{-1}) / \text{added straw} - \text{N amount (mg pot}^{-1}) \times 100 \quad (7)$$

$$\text{Straw} - \text{N loss rate (\%)} = (5) / \text{added straw} - \text{N amount (mg pot}^{-1}) \times 100 \quad (8)$$

All analyses were performed by the statistical package SPSS 17.0 software. A two-way ANOVA was performed to test the interactive effects of water management and N fertilization on the allocation and contribution of straw-N in the soil-plant system at both growth stages. The data were individually compared using the least significant difference test (LSD) at the 0.05 level of probability. The figures were drawn with Origin Pro. 8 software.

3. Results

3.1. Straw-N Release

The straw-N amount in the undecomposed straw declined markedly before PI and then slowed down; 44.10–66.47 mg pot^{−1} and 20.04–40.77 mg pot^{−1} at PI and MS (day 48 and day 133 after straw incorporation), respectively (Table 1). Compared to the CF treatment, the AWD treatment had a greater straw-N amount in the undecomposed straw at both growth stages, whereas N fertilization treatment only significantly affected the straw-N amount in the undecomposed straw at MS, N₁ > N₀ (27.78 mg pot^{−1} vs. 37.01 mg pot^{−1}).

Table 1. Straw-N amount in undecomposed straw under different treatments (mg pot^{−1}).

Treatment	Initial	Panicle Initiation Stage (PI)	Mature Stage (MS)
CF-N ₀	304.20	44.10c	40.77a
AWD-N ₀	304.20	66.47a	33.25b
CF-N ₁	304.20	58.17b	20.04c
AWD-N ₁	304.20	57.57b	35.52b
Average ^a			
CF	304.20	51.14	30.40
AWD	304.20	62.02	34.38
N ₀	304.20	55.29	37.01
N ₁	304.20	57.87	27.78
ANOVA analysis		F (p)	F (p)
W		59.51 (<0.001)	13.22 (<0.01)
N		3.34 (0.11)	71.22 (<0.001)
W × N		66.31 (<0.001)	110.47 (<0.001)

Panicle initiation stage and mature stage represent day 48 and day 133 after straw incorporation, respectively. CF: conventional flooded irrigation, AWD: alternate wetting/drying irrigation; N₀: without N fertilization N₁: with N fertilization addition, W: water management; N: N fertilization level, W × N: interaction of water management and N fertilization. ^a: values are averaged across N fertilization level or water management. Different letters in a column indicate the significant difference at $p < 0.05$ between different treatments.

Moreover, the straw-N release was significantly affected by the interaction of water management and N fertilization (W × N) at both growth stages. For example, N fertilization addition under the AWD condition significantly reduced 11.89% of the straw-N amount in the undecomposed straw at PI, but no difference was observed at MS. Inversely, the AWD treatment under the N₁ condition did not influence the straw-N amount in the undecomposed straw at PI but was higher at MS than the CF treatment.

3.2. Straw-N Accumulation and Its Contribution to N Uptake in Rice Plants

Straw-N accumulation in the whole plant was 27.97–36.03 mg pot^{−1} and 31.04–41.91 mg pot^{−1} at PI and MS, which was significantly affected by N fertilization only (Table 2). The N₁ treatment had a greater straw-N accumulation in the whole plant (35.84 mg pot^{−1} and 41.65 mg pot^{−1}) than the N₀ treatment (29.53 mg pot^{−1} and 31.66 mg pot^{−1}) at both growth stages. Further analysis found that straw-N accumulation in various plant parts overall decreased in the order of root > stem–leaf at PI, and panicle > root > stem–leaf at MS, which were significantly impacted by water management, N fertilization, and their interaction. Compared to the CF treatment, the AWD treatment under the N₀ condition markedly increased straw-N accumulation by 16.29% in the root at PI, 36.31%, and 44.45% in the stem–leaf and panicle at MS, respectively, but decreased by 43.96% in the root at MS. However, under the N₁ condition, the AWD treatment had the higher straw-N accumulation in the root and the lower in the shoots (including stem and leaf and/or panicle) than the CF treatment at both growth stages.

Contribution of straw-N to N uptake of the whole plant accounted for 4.52–7.70% and 2.43–4.59% at PI and MS, with decreasing order of root > stem–leaf or panicle (Table 3). Water management and N fertilization had a significant interaction effect on the straw-N

contribution rate in various plant parts and whole plant. For example, except for the roots, the AWD treatment under the N_0 treatment condition showed a higher straw-N contribution rate in the various plant parts and both growth stages than the CF treatment, increasing the straw-N contribution rate in the whole plant by 89.06% and 42.43% at PI and MS. Inversely, under the N_1 condition, the AWD treatment increased the straw-N contribution to the total N of roots by 3.34% and 16.08% at PI and MS, but significantly decreased the proportion of straw-N in total N of stem-leaf, panicle, and whole plant. Furthermore, N fertilization addition combined with the CF or AWD treatment had a lower straw-N contribution rate in the various plant parts; similar trends were observed at the two growth stages.

Table 2. Straw-N accumulation in various plant parts under different treatments (mg pot^{−1}).

Treatment	Panicle Initiation Stage (PI)			Mature Stage (MS)			
	Root	Stem-Leaf	Whole Plant	Root	Stem-Leaf	Panicle	Whole Plant
CF- N_0	15.16c	12.81b	27.97c	13.74a	5.48c	11.81c	31.04b
AWD- N_0	18.11b	12.99b	31.10b	7.77c	7.47b	17.06b	32.29b
CF- N_1	15.48c	20.55a	36.03a	9.55b	10.14a	22.22a	41.91a
AWD- N_1	21.75a	13.90b	35.65a	13.14a	9.73a	18.52b	41.39a
Average ^a							
CF	15.32	16.68	32.00	11.65	7.81	17.02	36.47
AWD	19.93	13.44	33.37	10.45	8.60	17.79	36.84
N_0	16.63	12.90	29.53	10.76	6.47	14.44	31.66
N_1	18.61	17.23	35.84	11.35	9.93	20.37	41.65
ANOVA analysis	F (p)	F (p)	F (p)	F (p)	F (p)	F (p)	F (p)
W	65.55 (<0.001)	21.60 (0.002)	2.85 (0.130)	26.57 (0.001)	5.52 (0.047)	1.43 (0.266)	0.24 (0.639)
N	12.08 (0.008)	38.67 (<0.001)	59.79 (<0.001)	6.52 (0.034)	105.79 (<0.001)	84.71 (<0.001)	172.21 (<0.001)
W × N	8.55 (0.019)	24.12 (0.001)	4.62 (0.064)	428.33 (<0.001)	12.64 (0.007)	48.09 (<0.001)	1.35 (0.278)

Panicle initiation stage and mature stage represent day 48 and day 133 after straw incorporation, respectively. CF: conventional flooded irrigation, AWD: alternate wetting/drying irrigation; N_0 : without N fertilization N_1 : with N fertilization addition, W: water management; N: N fertilization level, W × N: interaction of water management and N fertilization. ^a: values are averaged across N fertilization level or water management. Different letters in a column indicate a significant difference at $p < 0.05$ between different treatments.

Table 3. Contribution of straw-N to total N of various plant parts under different treatments (%).

Treatment	Panicle Initiation Stage (PI)			Mature Stage (MS)			
	Root	Stem-Leaf	Whole Plant	Root	Stem-Leaf	Panicle	Whole Plant
CF- N_0	18.41a	4.07b	7.06b	13.76a	2.72b	3.10b	4.54a
AWD- N_0	16.31b	4.44a	7.70a	10.44b	3.59a	4.06a	4.59a
CF- N_1	14.59c	3.85c	5.64c	9.02c	2.41b	2.40c	2.88b
AWD- N_1	15.07c	2.16d	4.52d	10.47b	1.87c	1.75d	2.43c
Average ^a							
CF	16.50	3.96	6.35	11.39	2.56	2.75	3.71
AWD	15.69	3.30	6.11	10.46	2.73	2.90	3.51
N_0	17.36	4.25	7.38	12.10	3.15	3.58	4.57
N_1	14.83	3.00	5.08	9.74	2.14	2.07	2.65
ANOVA analysis	F (p)	F (p)	F (p)	F (p)	F (p)	F (p)	F (p)
W	5.27 (0.051)	98.19 (<0.001)	2.09 (0.186)	5.04 (0.055)	2.96 (0.124)	7.33 (0.027)	8.97 (0.017)
N	5.61 (<0.001)	349.81 (<0.001)	196.14 (<0.001)	32.21 (<0.001)	111.64 (<0.001)	689.64 (<0.001)	801.96 (<0.001)
W × N	13.35 (0.006)	237.78 (<0.001)	28.82 (<0.001)	33.04 (<0.001)	54.02 (<0.001)	196.51 (<0.001)	14.30 (0.005)

Panicle initiation stage and mature stage represent day 48 and day 133 after straw incorporation, respectively. CF: conventional flooded irrigation, AWD: alternate wetting/drying irrigation; N_0 : without N fertilization N_1 : with N fertilization addition, W: water management; N: N fertilization level, W × N: interaction of water management and N fertilization. ^a: values are averaged across N fertilization level or water management. Different letters in a column indicate a significant difference at $p < 0.05$ between different treatments.

3.3. Straw-N Residue in Soil

Over time, residue straw-N amount in the soil showed an increasing trend, rising from 101.73–131.05 mg pot^{−1} at PI to 102.42–213.44 mg pot^{−1} at MS, which were significantly affected by water management and N fertilization, but there was no interaction between the two at both growth stages (Table 4). Compared to the CF treatment, the AWD treatment had more straw-N retention in the soil under both N₀ and N₁ treatments at PI and MS. However, the effect of N fertilization addition on the residue straw-N amount in the soil showed an opposite trend at different growth stages, with an average decrease of 6.28% ($p = 0.048$) at PI but an average increase of 66.77% ($p < 0.001$) at MS.

Table 4. Amount of straw-N in soil and its contribution to the soil N pool under different treatments.

Treatment	Panicle Initiation Stage (PI)		Mature Stage (MS)	
	Straw-N (mg pot ^{−1})	Ndfs (%)	Straw-N (mg pot ^{−1})	Ndfs (%)
CF-N ₀	103.33c	0.62b	102.42d	0.63d
AWD-N ₀	131.05a	0.75a	133.41c	0.84c
CF-N ₁	101.73c	0.73a	186.94b	1.17b
AWD-N ₁	117.91b	0.69ab	213.44a	1.36a
Average ^a				
CF	102.53	0.67	144.68	0.90
AWD	124.48	0.72	173.43	1.10
N ₀	117.19	0.69	117.92	0.73
N ₁	109.82	0.71	200.19	1.26
ANOVA analysis	F (p)	F (p)	F (p)	F (p)
W	48.35 (<0.001)	4.42 (0.069)	59.47 (<0.001)	68.41 (<0.001)
N	5.46 (0.048)	0.90 (0.371)	487.18 (<0.001)	470.03 (<0.001)
W × N	3.34 (0.105)	13.61 (0.006)	0.37 (0.563)	0.22 (0.649)

Panicle initiation stage and mature stage represent day 48 and day 133 after straw incorporation, respectively. Ndfs: the percentage of soil N content derived from straw-N. CF: conventional flooded irrigation, AWD: alternate wetting/drying irrigation; N₀: without N fertilization N₁: with N fertilization addition, W: water management; N: N fertilization level, W × N: interaction of water management and N fertilization. ^a: values are averaged across N fertilization level or water management. Different letters in a column indicate a significant difference at $p < 0.05$ between different treatments.

The percentage of straw-N to total N in the soil was 0.62–0.75% and 0.63–1.36% at PI and MS, respectively (Table 4). Compared to the treatment of CF and N₀, the AWD and N₁ treatment increased the percentage of straw-N within the total N of the soil, especially at MS ($p < 0.001$). Furthermore, we observed that water management and N fertilization had a significant interaction on the percentage of straw-N to soil total N content at PI, but they showed no interaction effect at MS, with a decreasing order of AWD-N₀, CF-N₁ > AWD-N₁ > CF-N₀ at PI, and AWD-N₁ > CF-N₁ > AWD-N₀ > CF-N₀ at MS.

3.4. Distribution of Straw-N in the Soil–Plant System

At PI and MS, the whole plant recovery rate (shoot + root) and soil residual rate of straw-N were 9.20–11.85% and 10.20–13.78%, and 33.46–43.11% and 33.67–70.16%, respectively (Figure 2). The straw-N loss was significantly impacted by water management, N fertilization, and their interaction (Table S3 in Supplementary Materials). Compared to the CF treatment, the AWD treatment significantly reduced the straw-N loss rate at PI and MS with and without N fertilization addition. N fertilization addition did not impact the straw-N loss rate at PI but was markedly reduced by 299.34% at MS under the AWD condition.

Figure 2. Distribution of straw-N at PI (A) and MS (B) in the soil–plant system.

4. Discussion

4.1. Utilization of Straw-N in the Soil–Rice System

In our study, on average, 89% of plant total straw-N absorption was observed before PI. This was because the increase of N uptake by the plant was related to the enhancement in supply amount [7,28,36]. The rapid release phase of straw-N always occurred at the early stage of straw incorporation [30]. Guan et al. found that half of the wheat straw-N released on day 31–35 after returning in a field situ experiment [35] was similar to this study results depicting 72–77% of the wheat straw-N release rate at PI (day 48 after straw incorporation). Straw-N could play a greater role in the early growth of rice, such as root growth, because about 50% of the absorbed straw nitrogen was accumulated in the root at PI.

Uptake by the plant and retention in the soil represent two effective pathways of straw-N utilization in a soil–plant system [7,8]. In our study, the wheat straw-N recovery rate in the whole plant and soil was 10.2–13.8% and 33.7–70.2%, respectively, at MS; the former was smaller than the latter. These results were consistent with previous studies in the paddy (7.7–24.6% and 33.1–77.5%, respectively) [7,10] and dryland fields (4.6–23.5% and 55.6–85%, respectively) [8,9]. Previous findings have shown that the straw-N existing in the soil aggregates in the organic form [33,38], which is harder for plants to take up and lose compared to fertilizer-N [7]. Chen et al. reported that the straw-N recovery rate after the first and second growing season was 92.0% and 85.6%, respectively [7]. Ding et al. also observed that the straw-N residual rate in mineral N and microbial biomass N after the third growing season was less than 3% [36]. These results suggest that residual straw-N in the soil might represent long-term retention in the soil N pool and slowly transfer to the plant by mineralization.

4.2. Effect of Water Management on the Allocation of Straw-N in the Soil–Rice System

Our results showed that AWD gave a similar straw-N absorption in the whole plant but markedly changed the straw-N allocation in various plant parts compared to CF. This was because AWD altered the growth center strength. The allocation of N in plants always depended on the strength of the growth center. High straw-N accumulation in the roots in AWD at PI was attributed to the aeration achieved through the AWD, which increased soil oxygen capacity and thus contributed to the decomposition of organic acids, the detoxification of root, and the improvement of root N absorption capacity [19,22,23,39]. In our study, the roots-to-shoots ratio of AWD was relatively high compared to CF at PI, but decreased at MS, showing that AWD altered the growth center strength (Table S2). This might explain the small straw-N accumulation in the roots of AWD at MS. AWD had a great ability to transfer absorbed N to shoots during the reproductive period, increasing the N use efficiency [18,21,22,40].

A positive effect of AWD on straw-N residue in soil and straw-N loss reduction was observed in our study. The present study and previous research might provide several reasons: First, a good soil physical condition in AWD increased microbial community activity [41,42], which might promote straw-N in organic form to associate with soil aggregates. Second, mitigation of the straw-N release rate in AWD might be due to lower water moisture in a dry cycle [29], leading to lower soil mineral N derived from straw-N, which might reduce straw-N loss in the form of ammonia volatilization. The intensity of N₂O emission in the paddy field depended on the soil substrate concentration and soil moisture [43]. N₂O flux in mid-season drainage and final drainage was substantially higher than dry cycle in AWD [44], while these drainage practices were applied among all treatments in our study. Therefore, the response of straw-N loss by gas emission to water management needs further study. Third, reduction of irrigation and increasing the biomass of rice roots and shoots (Table S2) could indirectly alleviate N loss by runoff and leaching [25,26]. Therefore, AWD is an excellent water measure to synergize the efficient use of exogenous N and save on irrigation.

4.3. Effect of N Fertilization on the Allocation of Straw-N in the Soil–Rice System

N fertilization addition promoted straw-N transfer to the plant, which was consistent with previous studies [8,36]. However, we found that N fertilization addition increased the final straw-N residue rate in soil and reduced the straw-N loss. These findings were in disagreement with the dryland system's results [8,36], which might be due to the higher runoff in paddy systems than dryland [37], whereas successfully reducing surface runoff with N fertilization was due to high biomass (Table S2) and strong transpiration capacity. Furthermore, soil microbe activity and abundance directly controlled the mineralization of soil organic N [29,41]. In this case, fertilizer-N was assimilated immediately by soil microbes after inorganic N fertilization addition and then released in an available state for uptake by the plant [7,45]. Meta-analysis results suggested that inorganic N fertilization addition could decelerate the mineralization of soil organic N [15] (including organic N derived from straw-N). The weakening of volatilization, nitrification, and denitrification with decreasing mineral N content could effectively alleviate N loss by gas emission, runoff, and leaching [13,26,44]. Furthermore, under N_1 condition, straw-N loss at PI was higher than MS, which might be because straw-N loss in our study was assessed by the N balance method rather than obtained by direct measurement. In this case, the accumulation of small differences in the measurement values of plant uptake, soil residue, and undecomposed straw might cause this abnormal value. However, temporal variation of straw-N loss was not the focus of this study, so it did not explain too much.

4.4. Effect of Water Management Combined with N Fertilization on the Allocation of Straw-N in the Soil–Rice System

Prior to this study, little information was available to describe if and how AWD interacted with N fertilization on straw-N utilization in a soil–rice system. Interestingly, we found that AWD and N fertilization addition had no interactive effect on the straw-N recovery rate in the whole plant and soil but had a positive interactive effect on the root's straw-N absorption and negatively impacted the shoot's straw-N absorption. Generally, a high level of N fertilization (such as with 300 kg N ha^{-1} in this study, which is higher than the global average N fertilization level of 115 kg N ha^{-1} [46]) could cause soil acidification both directly and indirectly [47]. The observation data of Nuno et al. showed that N fertilization application caused soil acidification in drainage, but it had no effect on the soil pH of the paddy field during the flooding condition [48]. Under acidic conditions, plants have a higher capacity to acquire organic N such as amino acids and amino acid residues [49,50]. Some studies have noted that the transfer rate of amino acid N from roots to shoots was slower than that of NO_3^- -N [49,51]. In this case, we speculated that more small-molecule organic N derived from straw-N in the interaction of AWD and N fertilization addition might be metabolized and assimilated by roots, leading to more straw-N retention in the root. It was suggested that AWD combined with N fertilization addition could facilitate rice root development under straw incorporation conditions (Table S2), which is favorable for the absorption and utilization of N [21,40,52] and strengthens rice lodging resistance.

In general, the maximum uptake of nutrients and water by the root occurred during the period of PI to MS (Table S2) [22,53], suggesting that intense biochemical progress in soil took place during this period. Our study found that the difference in the soil straw-N among the treatments was mainly observed during this period. Seasonal dynamic monitoring showed that the difference in soil NH_4^+ -N and total N concentration among different water management after the jointing booting stage (namely PI in our study) was higher than before the jointing booting stage, and the change of NO_3^- -N concentration mainly occurred at jointing booting stage [24,26]. It suggested that water management strongly interfered with the soil N cycle after PI. Adding inorganic fertilizer N to soil could effectively avoid mineralization of soil organic matter [15], including soil aggregate associated straw-N, which might reduce straw-N loss. Therefore, AWD combined with N fertilization addition under straw incorporation conditions can improve soil fertility.

In China, conventional flooding irrigation is still used by farmers under straw incorporation conditions, resulting in water and nutrients waste and yield loss [21,25,44]. In our results, a positive interactive effect between AWD and N fertilization addition on the mitigation of straw-N loss indicated that this integration treatment is a valuable straw resource utilization measure. Therefore, amended water management could not only save irrigation but also improve the soil fertility and the ability of roots to absorb nutrients [17,21]. However, N fertilization addition might be the “double-edged sword” as the excessive accumulation of soil mineral N could increase the risk of fertilizer-N loss and soil acidification [54,55]. Thus, it is necessary to further explore the appropriate N fertilization rate to synergize the effective utilization of fertilizer-N and straw-N, achieving sustainable agricultural development.

5. Conclusions

In the rice–wheat system, the wheat straw-N of the plant recovery rate and the soil residual rate was an average of 12.0% and 52.3%, respectively, after the rice harvest. This study also determined that AWD increased straw-N accumulation and contribution in roots and soil but did not influence straw-N absorption in the whole plant. N fertilization addition markedly enhanced the straw-N amount in various plant parts and soil, despite the lower contribution of straw-N to the N uptake of rice. Above all, this study strengthens the systematic understanding of how water management and N fertilization interact to affect the dynamics of wheat straw-N allocation in the soil–rice system, showing that AWD combined with N fertilization addition has a more positive effect on the effective utilization of straw-N and the mitigation of its loss in the soil–rice system.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy11040750/s1>, Table S1: ANOVA analysis of the allocation of straw-derived N in the soil–rice system. Table S2: Biomass in different parts of rice under different treatments (g pot^{-1}). Table S3: Total N absorption in different parts of rice under different treatments (mg pot^{-1}).

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