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Combined Effects of Soil Water Regimes and Rice Straw Incorporation into the Soil on ^{15}N, P, K Uptake, Rice Yield and Selected Soil Properties

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Author's contributions

This work was carried out in collaboration between both authors. Author AMG designed the study, wrote the protocol, performed the experimental process and wrote the first draft of the manuscript. Author AIE managed the analysis of the experiment and literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Understanding the effects of water regimes on nutrient uptake of rice plants, especially by different organic fertilizers is critical to improve long-term rice productivity. In a greenhouse experiment, the effects of soil water management and incorporation of rice straw into the soil on nutrient uptake, soil properties and rice productivity were studied in a clay soil. The treatment included two levels of soil water regimes (continuous submergence and alternate submergence-drying) and four rice straw levels (0, 5, 10 and 15 t ha^{-1}). Results showed that, soil pH decreased slightly with increasing rate of rice straw application in both continuous submergence and alternate submergence-drying. Soil Eh values were correlated to rice straw application levels. Alternate submergence-drying in rice plant for some period of time significantly increased rice growth parameters and rice yield. Nitrogen

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in rice plant was derived mostly from fertilizer (higher N_{dff}) values in continuous submergence and alternative submergence-drying. The highest ^{15}N atom% values in plant were observed at panicle initiation stage under both water regimes. Most of ^{15}N uptake by rice plant was from the soil (averaged 53%). The uptake of P, K and Zn nutrients was greater in continuous submergence than in alternate submergence-drying.

Keywords: Rice straw residues; alternative water management; rice growth; soil properties.

1. INTRODUCTION

Organic matter plays a key role in soil fertility and productivity. It provides nutrients to the soil and helps it to maintain better aeration for seed germination and plant root development [1]. Application of organic residues and manures, such as rice straw and sewage sludge improves soil organic matter content, soil structure, water holding capacity and enhance nutrients statues and increases microbial activities in the soil [2,3]. However, the continuous application of organic wastes in soil may lead to accumulation of soluble salts and heavy metals in excess of amounts that can be removed by the crop, hence causing nutrients imbalance and toxicity in soil [4]. The role of soil organic matter as a source of nutrients, especially N, P and S, through mineralization has long been documented. [5] Found that nutrient supplied through soil organic matter mineralization can lead to a decrease in inorganic fertilizer requirements of crops.

Rice straw is the major bi-product source in Egyptian rice fields. Incorporation of rice straw and remaining stubble into the soil returns some of the nutrients and helps to maintain rice grain yield over the long-term period. Straw incorporation has been reported to improve soil physical condition and rice plant growth. The direct effect of N from organic residue on the cropping system could either result in yield decrease due to immobilization of N during decomposition or no effect due to insufficient quantities of crop residues [6] or to an increase in yield due to rapid release of N [7]. Effect of rice straw on soil conservation and soil moisture retention and their mechanisms have been reported [8]. Incorporation of rice straw residues into soil can substantially reduce the amount of inorganic fertilizers used as such is a valuable management practice from both environmental and economic viewpoint.

Availability of water for agriculture, in particular for rice production, is threatened in many regions of the world by limitations of water resources [9]. So, it is necessary that water saving methods be considered and used for rice production. Reducing the amount of water-use for rice production is still controversial since there are critical issues associated with yield loss. Water deficit during the vegetative stage can reduce plant height, tiller number, leaf area, and grain yields. The duration of water stress is more important than the plant growth stage at which the stress occurs. Intermittent drying or keeping soils saturated during the growing season either vegetative or reproductive phase reduce rice yields significantly in most tropical rice fields. However, in some parts of China, Japan, and Korea, intermittent wetting and drying cycle during rice growing season governs rice yields, because organic and inorganic toxins accumulated from the decomposition under low soil temperature at early growing season is diminished.

The objectives of this research were a) to monitor soil pH and Eh changes as affected by water regime and rice straw application b) to quantify N, P, K and Zn uptake under different flooding management, c) to investigate the combined effect of water regime and rice straw application on some selected soil properties, rice yield and its components.

2. MATERIALS AND METHODS

2.1 Site, Climate and Soil Samples

The greenhouse experiment was conducted at the Rice Research and Training Center, Sakha, Kafr El-Sheikh, Egypt (31°6′ 42″ N, 30°56′ 45″ E). The area is characterized by minimum night temperature of 20°C and, day time maximum temperature of 33°C and relative humidity of about 50%. A clay soil was collected, dried, crushed and thoroughly mixed. The selected soil physical and chemical properties and methods of analysis used are given in Table 1.

2.2 Treatments and Design

Plastic pots were filled with 8.50 kg air-dried soil. The experiment was set up as a split-plot design with water regimes (two) as main plots and application rates of rice straw (four) as sub plot (0, 5, 10 and 15 ton ha^{-1}) with four replicates. Rice straw has the following chemical properties: pH (H_2O) 6.10, total N (0.28%), total P (0.13%), total K (1.59%) and total C(45.1%). Phosphorus as P_2O_5 and K as KCl were applied as a basal dose to all pots at the rate of 80 kg ha^{-1} just before transplanting. Chemical nitrogen fertilizer ($^{15}NH_4Cl$, 3.0 atom %) was applied at rate of 150 Kg ha^{-1} added at 4 and 8 weeks after planting. Four,25-day-old seedlings of rice cultivar Sakha 105 were transplanted into the center of each pot. After the seedlings establishment, plants were thinned to three per pot and two water management regimes: Continuous submergence (CS) and alternate submergence-drying (ASD). The soil under CS treatment was kept continuously submerged and 4 cm standing water during the experiment [18]. In alternate submergence-drying (ASD) treatment, soil received appropriate water to bring the soil just to saturation and the moisture soil content was maintained by weighting the pots every day [19].

Table 1. Some physical and chemical characteristics of surface (0-20cm) soil used in study (n=4)

Particulars	Method	Value
pH ($_{\text{soil paste}}$)	[10]	7.15
EC (dS m^{-1})	[11]	1.70
Total N (g kg^{-1})	[12]	0.05
Available-P (mg kg^{-1})	[13]	20
Available-K (g kg^{-1})	[14]	0.03
DTPA-Zn (mg Kg^{-1})	[15]	0.19
Clay %		55
Sand %	[16]	11
Silt %		34
Organic matter (%)	[17]	2.0

2.3 Plant Samples

Plant height, number of tillers and dry weight, were recorded at maximum tillering, panicle initiation and maturity growth stage. The dry weight of grain yield was recorded. Subsamples of plants were selected randomly to determine yield attributes such as panicle weight, filled and unfilled grains per panicle and number of panicles.

2.4 Determination of Soil Eh and Soil pH

Soil redox potential (Eh) of rhizosphere was determined in situ with redox meter. Soil pH values were recorded weekly from the plot establishment until 9 weeks after planting via pH meter.

2.5 Nutrient Uptake and ^{15}N Determination

The dried plant samples were weighed and ground into a fine powder using a vibrating mill. Total N and ^{15}N concentration in rice samples were determined by Isotope Ratio Mass Spectrometer (ANCA–SL; PDZ Europa Ltd., Cheshire, UK). Total N, P, K and Zn were calculated at the stage of rice maturity. Nitrogen derived from fertilizer (N_{dff}%) and nitrogen derived from soil amended with rice straw(N_{dfs}%)was calculated using the equation of [20] :

$$N_{dff}\% = {}^{15}N\% \text{ excess in plant sample}/{}^{15}N\% \text{ excess in labeled fertilizer}) \times 100.$$

$N_{dfs}\%$ = 100- $N_{dff}\%$ %, assuming that the rice crop has only three sources of plant nutrients namely fertilizer, rice straw and soil.

2.6 Soil Samples and Chemical Analysis

At the end of experiment, represented soil samples were collected from all treatments, air-dried, crushed, sieved (2-mm) and analyzed for organic matter content, soil pH, available P and available Kusing the methods described in Table 1. Reagent blanks and internal standards were used where appropriate to ensure accuracy and precision in chemical analysis.

2.7 Statistical Analysis

Statistical analysis was used to test variations between treatments, and the least significant difference using the software Ky Plot (Kyens Lab Inc., Tokyo, Japan).

3. RESULTS AND DISCUSSION

3.1 Soil pH and Eh Changes

Initial soil pH was 7.15 (Table 1). Generally, pH values of the soil solution were similar in both CS and ASD water regimes (Fig. 1). Lower pH values were observed in treatments that received higher rice straw application rates. Rice straw addition strongly affected soil pH values up to 4 weeks after planting. Thereafter, soil pH in both CS and ASD fluctuated till the end of the experiment. The decrease in soil pH values after application of rice straw was also reported by

[21,22]. The decrease in pH changes after incorporation of rice straw could probably be attributed to nitrification of N-NH_4^+ions or release of protonated H^+ ions during mineralization of the rice straw [23]. Similarly [24] reported decreases in soil pH following the addition of organic amendments. However, [25] reported organic amendments have a little effect on soil pH values. This reflects the variations of the initial chemical composition of the decomposing material. Organic residue can influence soil pH through accumulation of CO_2 and organic acid during their decomposition into soils [26]. The data of soil Eh showed that for all rates of rice straw incorporated into soil, Eh values ranged from -200 mV to +350 mV for the first days of irrigation (Fig. 2). After that Eh values of soil solution decreased dramatically, being lowest for the highest rate of rice straw applied. Values of Eh under both CS and ASD treatments was correlated negatively with the rice straw application rates, whereas increasing the rate of rice straw application resulted in lower soil Eh. However water regime, had little effect on soil Eh changes.

3.2 Uptake of ^{15}N

Results of ^{15}N atom% values in plant at different rice growth stages showed that increasing the application rate of rice straw resulted in significantly ($P < 0.05$) reduced and diluted ^{15}N fertilizer (Table 2). The highest ^{15}N atom% values in plant were observed at panicle initiation stage under both CS and ASD treatments. Total N content in plant samples increased with increasing application rates of rice straw in both CS and ASD treatment. This could be attributed to rice straw being an additional N source for the plant.

Total N content was in the order: Tillering> panicle initiation>maturity. There was no effect of water regime on ^{15}N atom%. Nitrogen derived from fertilizer (N_{dff}%) values was higher in CS than ASD treatment at the different rice growth stages. Higher rates of rice straw application resulted in higher N_{dff}% values in both CS and ASD treatment. The highest N_{dff}% values were observed under CS and ASD at panicle initiation stage. Values of nitrogen derived from soil (N_{dfs} %) were similar to N_{dff}% values under both CS and ASD conditions. Also, N_{dfs} % increased with increasing rice straw application (Table 3). The order of N_{dfs}% was tillering>maturity> panicle initiation. The results showed that most of the ^{15}N uptake by rice plant was from the soil and ranged between 36 to 70% which agrees well with the results of [27].

3.3 Nutrient Uptake

Rice straw application significantly affected the uptake of N, P, K and Zn by rice plants at maturity under both CS and ASD water treatments (Table 3). Under ASD treatment, incorporation of rice straw into soil significantly increased the shoot N, P, K and Zn uptake. However, increased uptake of these nutrients was lower under CS when compared to ASD treatment. These results suggest that CS water regime counteracted the effectiveness of rice straw application through improving the nutrient uptake by rice shoot [24,3].

3.4 Rice Growth Parameters

Among the rice yield components, number of tillers and plant height were significantly influenced by different water regimes and rice straw application rate (Table 4). Higher application rates of rice straw (≥5 tha^{-1}), significantly decreased the number of tillers and plant height growth parameters. However, the number of tillers under ASD was not significantly different among increasing rice straw application levels. At different rice growth stages, plant dry weight increase significantly with increasing rice straw application rates. ASD water regime, resulted in significantly greater dry weight production compared to CS.

3.5 Yield and Yield Components

The data of yield and yield attributes a represented in Table 5. There were significant effects of rice straw application and water regimes on yield and yield attributes of rice. The data of yield components (panicle weight, number of panicle, filled grains and grain yield) were higher under ASD than CS treatment. Also increasing the rate of rice straw application resulted in increasing yield and yield attributes. The increases in rice yield could be attributed to the release of nutrients from the rice straw residue during mineralization [28]. Under CS treatment, rice grain yield tended to be low compared with ASD treatment, which could be partially attributed to unfavorable conditions and partially due to limited rice growth during the vegetative phases submergence of rice fields cause major chemical changes in soil that affect nutrients transformation.

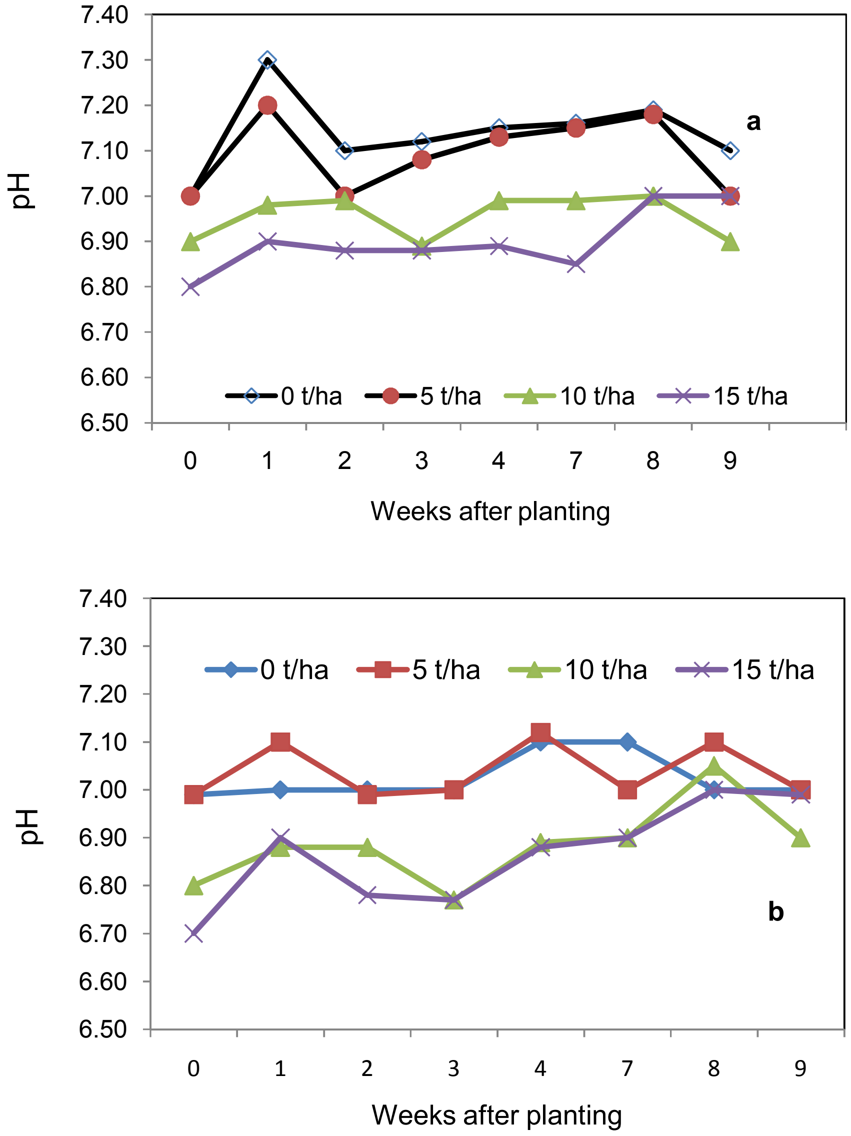

Fig. 1. Effect of water regimes and rice straw application on pH changes under (a) continuous submergence and (b) alternate submergence-drying

3.6 Soil pH and Organic Matter

Soil pH value increased slightly after harvest with increasing rate the rice straw application under both CS and ASD treatments (Table 6). Soil organic matter content (OM%) positively correlated with levels of rice straw application under both CS and ASD treatment. However, water regime had little effect on soil OM content. Increases in soil OM was attributed mainly to the continuous addition of carbon through roots and decomposition of rice crop residues [29,30]. Similar results were reported by [31]. In addition [32] also found significant increase in soil OM content with addition of rice straw and legume residue. Furthermore, [33] reported that incorporation of rice straw residue into soil for long periods (7 years) significantly increased organic carbon content of the sandy loam soil compared with either straw burning or removal. In another long-term study, wheat straw incorporation into soils increased organic carbon content from 0.40% in the control treatment to 0.53% in the wheat straw incorporation treatment [34].

3.7 Available Soil P and K

The effect of incorporation of rice straw on soil available P is presented in (Table 6). After harvest, incorporation of 15 t ha^{-1} rice straw residues resulted in significantly higher P values (89 mg kg^{-1} in CS and 95 mg kg^{-1} in ASD), respectively. Available soil P values were higher in CS than in AWD treatment. The incorporation of crop residues into soils may increase crop total-P either directly by the process of mineralization and subsequently release of P or indirectly by increase in the amount of soluble OM. This OM is mainly organic acids which increase the rate of desorption of phosphate and therefore, improving the available soil-P content. The long-term study on application of corn residues showed an increase in the levels of soil-P [35]. Ina decomposition study, [36-37] demonstrated that, organic-P in crop residues could provide a relatively labile-P to succeeding crops, thus, providing a larger pool of mineralizable soil organic-P and soluble inorganic-P pools The increases in available-P concentration in organic waste application with recommended chemical P-fertilizer could be attributed to high microbial activity induced by the addition of organic and inorganic-P soluble forms [25].

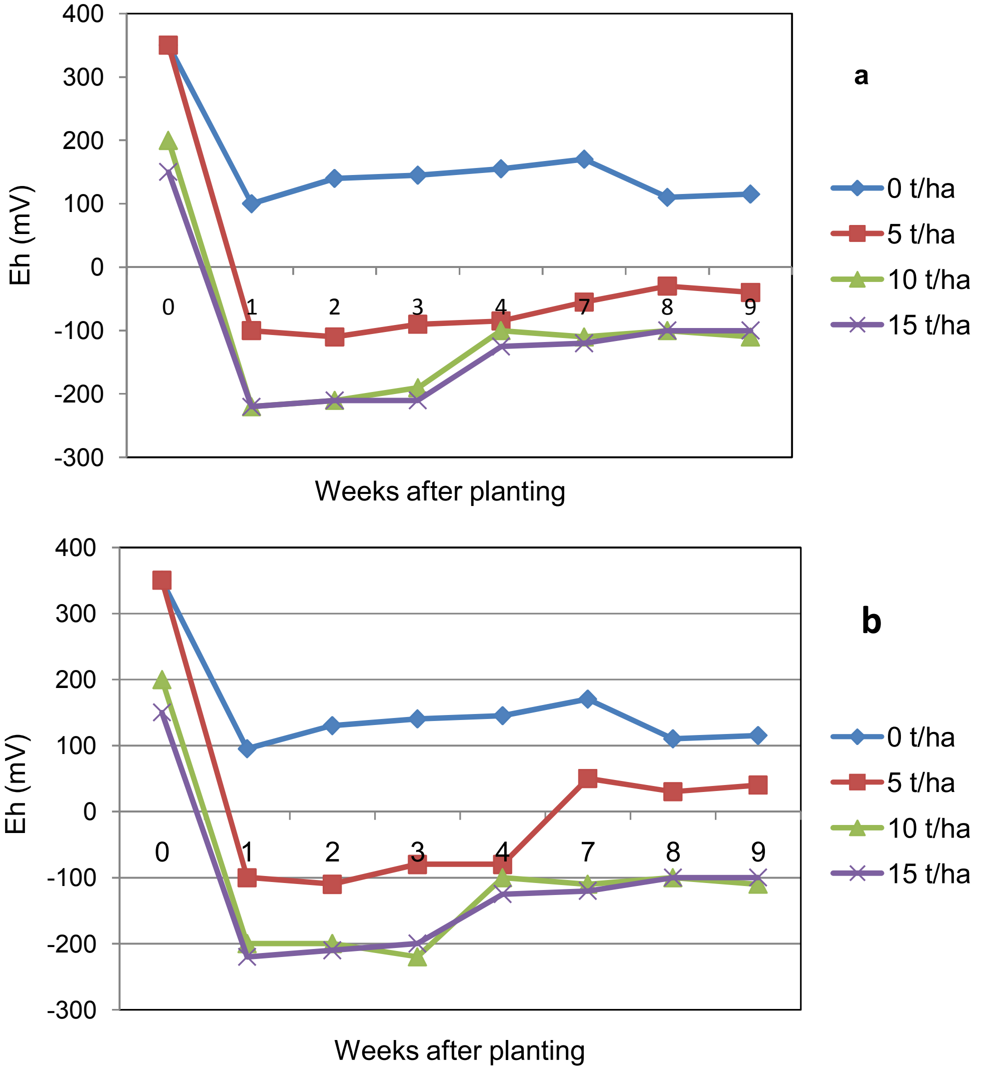

Fig. 2. Soil Eh values between 0-9 weeks after irrigation as effects of rate of rice straw incorporated into the soil and water regimes, a) continuously submergence and b) alternate submergence-drying

Table 2. Effect of water regime and rice straw application rate on N content, ^{15}N distribution, N derived from fertilizer and N derived from soil at different rice growth stages

Treatment	Nitrogen content (%)											
	Tillering stage				**Panicle initiation stage**				**Maturity stage**			
	Rate of rice straw (t ha^{-1})				**Rate of rice straw (t ha^{-1})**				**Rate of rice straw (t ha^{-1})**			
	0	**5**	**10**	**15**	**0**	**5**	**10**	**15**	**0**	**5**	**10**	**15**
Continuous Submergence (CS)	3.10b	3.25b	3.41b	4.20a	1.62b	1.62b	2.70a	2.60a	0.41a	0.40a	0.50a	0.52a
Alternate submergence-drying (ASD)	3.02a	3.28a	3.60a	3.71a	1.60a	1.66a	2.15a	2.10a	0.41a	0.42a	0.49a	0.50a
^{15}N atom % distribution												
Continuous Submergence (CS)	1.63a	1.66a	1.40b	0.99c	2.54a	2.55a	2.30b	1.90c	1.84a	1.71ab	1.67b	1.28c
Alternate submergence-drying (ASD)	1.50ab	1.60ab	1.31b	1.00c	2.61b	2.50a	2.44a	2.00b	1.84a	1.75a	1.77a	1.50b
Nitrogen derived from fertilizer (N_{dff}%)												
Continuous Submergence (CS)	36c	39c	45b	60a	50c	51c	63b	70a	50c	52c	56b	70 a
Alternate submergence-drying (ASD)	43ab	47a	37b	25c	59a	58ab	55b	46c	49a	47b	48ab	41c
Nitrogen derived from soil (N_{dfs}%)												
Continuous Submergence (CS)	50c	51c	63b	76a	36c	39c	45b	60a	50c	52c	56b	70a
Alternate submergence-drying (ASD)	57c	5 c	63b	75a	42c	45c	54a	51b	5c	53b	52c	59a

N_{dff}, Nitrogen derived fertilizer%; N_{dfs}, N derived from soil and rice straw = 100-N_{dff}. Means at each row, followed by the same letters are not significantly different by LSD test ($P \leq 0.05$)

Table 3. The main and interactive effects of soil water regimes and rice straw application on nutrient uptake by rice shoot (average ± standard deviation)

Water regime	**Rate of rice straw (t ha^{-1})**	**Nutrient uptake at rice maturity stage (g pot^{-1})**			
		N	**P**	**K**	**Zn**
Continuous Submergence (CS)	0	117b±1.8	20b±1.8	70d±1.5	0.24b±0.2
	5	120b±1.9	23a±1.6	100c±1.3	0.26a±0.1
	10	190a±2.0	24a±1.5	155b±1.4	0.27a±0.1
	15	210a±2.2	24a±1.3	172a±1.5	0.29a±0.2
Mean		**159**	**23**	**124**	**0.27**
Alternate submergence-drying (ASD)	0	180a±2.3	17b±1.1	70c±1.2	0.22b±0.2
	5	172a±2.1	17b±1.3	90b±1.2	0.26a±0.1
	10	170a±2.5	21a±1.1	130a±1.1	0.27a±0.3
	15	181a±2.3	22a±1.2	146a±1.5	0.28a±0.2
Mean		**175**	**19**	**109**	**0.26**

Means at each column, followed by the same letters are not significantly different by LSD test ($P \leq 0.05$)

Table 4. Effect of water regime and rice straw application rate on some growth characteristics at different growth stage of rice

	Number of tillers											
Treatment	**Tillering stage**				**Panicle Initiation stage**				**Maturity stage**			
	Rice straw rate (t ha^{-1})				**Rice straw rate (t ha^{-1})**				**Rice straw rate (t ha^{-1})**			
	0	**5**	**10**	**15**	**0**	**5**	**10**	**15**	**0**	**5**	**10**	**15**
Continuous Submergence (CS)	8a	9a	7b	4c	10a	9a	8a	8a	14b	16ab	13b	18a
Alternate Submergence-Drying (ASD))	9a	9a	8a	8a	10a	9a	9a	9a	15a	19b	20ab	25a
	Plant height (cm)											
Continuous Submergence (CS)	54a	55a	47c	48bc	85b	85b	92a	82a	84b	84b	91a	91a
Alternate Submergence-Drying (ASD)	50a	52a	52a	52a	62a	63a	72a	71a	83b	87b	96a	90b
	Dry weight (g)											
Continuous Submergence (CS)	2.15a	2.05a	1.08b	0.89b	8.96a	6.70b	5.90b	6.30ab	20.3b	23.3b	21.1b	37.1a
Alternate Submergence-Drying (ASD)	2.90ab	2.10b	2.00b	3.10a	23.6a	19.1b	19.0b	31.2a	24.4c	30.4c	36.4c	45.0a

Means at each column, followed by the same letters are not significantly different by LSD test ($P \leq 0.05$)

Table 5. Effect of water regime and rice straw application rate on rice yield and its components

Water regime	Rate of rice straw (t ha^{-1})	Panicle weight (g)	# of panicle	Filled grains/ panicle (g)	Unfilled grains/ panicle (g)	Grain yield (t ha^{-1})
Continuous Submergence (CS)	0	20.3b	12.8b	24.0ab	3.75b	4.80b
	5	22.3b	16.0ab	27.1a	4.35b	5.01b
	10	21.6b	13.0ab	18.1b	4.60ab	4.90ab
	15	38.3a	17.2a	24.1ab	6.10a	6.01a
Mean		**25.6**	**14.8**	**23.3**	**4.70**	**5.18**
Alternate submergence-drying (ASD)	0	28.0b	13.8c	23.1b	3.70c	7.00b
	5	41.3a	18.1b	36.1a	5.10bc	6.90b
	10	41.3a	19.0b	33.2a	5.60a	7.10b
	15	41.3a	24.0a	34.6a	5.01ab	8.01a
Mean		**37.9**	**18.7**	**31.7**	**4.85**	**7.25**

Means at each column, followed by the same letters are not significantly different by LSD test (P ≤ 0.05)

Table 6. The main and interactive effects of soil water conditions and straw application on available K, P, pH and organic matter after harvesting (average ± standard deviation)

Water regime	Rate of rice straw (t ha^{-1})	Available nutrient (mg kg^{-1})		pH	OM (%)
		K	P		
Continuous Submergence (CS)	0	33c±1.5	65a±0.9	7.10a±0.01	2.30b±0.1
	5	39bc±1.4	66a±11	7.30a±0.02	2.34b±0.1
	10	54a±1.4	76±1.1	7.40a±0.03	2.50a±0.2
	15	48ab±1.3	89a±1.2	7.60a±0.02	2.56a±0.3
Mean		**44**	**74**	**7.35**	**2.43**
Alternate submergence-drying (ASD)	0	31b±1.1	66a±1.3	7.11a±0.01	2.31a±0.3
	5	32b±1.2	59a±1.1	7.12a±0.01	2.50a±0.2
	10	35a±1.1	69a±1.1	7.16a±0.02	2.51a±0.2
	15	35a±1.05	95a±1.2	7.17a±0.03	2.56a±0.1
Mean		**33**	**73**	**7.14**	**2.47**

Means at each column, followed by the same letters are not significantly different by LSD test (P ≤ 0.05)

Incorporation of rice straw residue into soil resulted in higher available K values in both CS and ASD treatments. However, continuous submergence (CS) had significantly higher available K than alternative submergence-drying (ASD). The increase in available K from the addition of 15 t/ha rice straw application compared to the 0 t/ha was 12.9% and 45% under ASD and CS treatments, respectively (Table 6). [38] Found that the release of K from rice straw occurred at a fast rate, that within 10 days after incorporation, available soil K concentration increased from 0.05 g Kkg^{-1} in the untreated soil to 0.06 g K kg^{-1} dry soil in the straw-amended treatment. It's known that, K element was not bound with any organic compound in the plant material, and therefore, its release does not involve microorganisms. During the decomposition of rice straw, K concentration decreased from 1.30 to 0.28 and about 79% of the total K present in rice straw was released within one month after its incorporation into the soil and 95.3% of K from rice straw was mineralized by the end of about 4 months [38]. Incorporation of rice residue and farmyard manure into soil in an incubation study increased available- K, water-soluble and fixed- K [39].

4. CONCLUSION

The application of rice straw into soil, enhanced shoot uptake of N, P and Zn under both water management regimes. Alternate submergence-drying increased K uptake compared to continuous submergence. Understanding the effects of water management on rice root especially by different organic and inorganic fertilizers is critical and needed to enhance rice productivity.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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