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Effects of straw return and aeration on oxygen status and redox environment in flooded soil

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Abstract: To study the effects of straw return and aeration of the water layer on oxygen and redox status in the water column and at different depths in paddy field soil, a short-term incubation experiment was conducted with four treatments: (1) no straw return (NS); (2) straw return without aeration (S); (3) straw return and 30 minutes of aeration per day (SO_{30}); and (4) straw return and 90 minutes of aeration per day (SO_{90}). Compared to NS, S decreased dissolved oxygen (DO) and redox potential (ORP) by 23–58% and 47–53 mV, respectively, and increased active reducing substance (ARS) by 21–46% in the water and soil layers. The aeration treatments increased DO and ORP by 25–120% and 11–86 mV, respectively, and reduced ARS by 5–16% compared to S. The results indicated that straw return to paddy fields exacerbated hypoxia and reducing conditions in the soil. SO_{90} achieved better effects than SO_{30} in alleviating the negative impact of straw return by supplying more oxygen, but the effects weakened over time and with soil depth.

Keywords: air injection; anaerobic degradation; anoxic water; growth inhibitor; redox potential

Straw return is recognized as an effective method of straw utilization, which sequesters carbon and releases nutrient elements with the decomposition of straw (Wang et al. 2017a). Straw return can affect habitat suitability for soil pathogens or alter the community composition of the predators or parasites of major disease organisms (Palm et al. 2014). Hence, straw return has been widely used in China. However, some studies reported that straw return to paddy fields could affect the rice root system, particularly in early growth stages (Tolley et al. 1986). After irrigation, paddy soils are subjected to changes from an aerobic to an anoxic status and from an oxidizing environment to a reducing environment.

Oxygen status is essential to biological processes in paddy fields, and hypoxic conditions can limit root respiration and hinder the root system from absorbing and transporting nutrients. Dissolved oxygen (DO) is an important index of water quality, reflecting the oxygen status of paddy water. Redox potential (ORP) is an important index of redox properties and plays an important role in controlling nutrient availability, element cycling and ecological functions of agroecosystems (Khan et al. 2019). Furthermore, growing in hypoxic and strongly reducing environments, paddies are potentially exposed to high levels of active reducing substances (ARS) (e.g., Fe^{2+}, Mn^{2+} and H_2S), which affect rice growth and yield (Rout et al. 2014).

Therefore, it is supposed that the role of straw return in hindering rice growth is attributed to the exacerbated hypoxia and reducing conditions in the soil. Aeration irrigation, which is the process of adding oxygen into irrigation water, is an innovative technique. Previous studies proved that aeration had a significant impact on soil air permeability and

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could increase crop production (Sang et al. 2018). However, few observations have been reported on the utilization of aeration to mitigate unfavourable factors in paddy fields. In this study, a short-term incubation experiment was conducted to study the effect of (1) straw return on oxygen and redox status in waterlogged soil and (2) aeration on relieving hypoxia and reducing status after straw return.

MATERIAL AND METHODS

Experimental site. The incubation experiment was carried out in July 2019 at the Agriculture Ecology Experimental Field of Hohai University, Nanjing, China (31°54'N, 118°46'E). During the period of the experiment, the daily mean air temperature fluctuated between 27.7 °C and 34.3 °C. A plastic awning was used to avoid the influence of rainfall. The texture of the soil used in the experiment was clay loam, the pH (1 : 2.5; soil : water) was 7.12, and the organic carbon and total nitrogen (N) concentrations were 9.69 and 0.83 g/kg, respectively.

Experimental design. The experiment started on July 29, 2019, with four treatments: (1) no straw return (NS); (2) straw return without aeration (S); (3) straw return and 30 min of aeration per day (SO_{30}); and (4) straw return and 90 min of aeration per day (SO_{90}). Each treatment was repeated three times. Twelve plastic boxes (65 cm in length, 45 cm in width and 36 cm in height) were used to contain soils, and they were placed according to a complete random block design. Soil was collected from the 0–20 cm soil layer of the paddy field. After air drying, the soil was ground and sieved through a 5-mm sieve. Approximately 88 kg of soil was added to each container and carefully compacted to a depth of 25 cm at a density of 1.2 g/cm^3.

Straw was cut into pieces of approximately 3–5 cm in length. A total of 146 g straw pieces (equivalent to 5 t/ha) were added to each treatment with straw return and thoroughly mixed in the 0–10 cm soil layer to simulate a local field after rotary tillage. The organic carbon, total N content and C/N ratio of the straw were measured to be 350.5 g/kg, 3.82 g per kg, and 91, respectively. All treatments were irrigated daily to maintain a constant water depth of 10 cm. The DO, pH and ORP of the irrigated water were in the ranges of 5.78–6.32 mg/L, 6.91–7.12 and 187.11–210.65 mV, respectively. No nutrients were added to the containers. The aeration system consisted of an air compressor (ACO-818, Sensen Co. Ltd., China), isometric air hoses and porous materials (ACO-001, Sensen Co. Ltd., China), providing 5 L air per minute to each aeration treatment. The porous materials were submerged into the water layer (Figure 1). Air created by the air compressor goes through the porous materials and breaks into small air bubbles.

Samples and measurements. The DO and ORP in the water layer and the 0–10 and 10–20 cm soil layers were measured every three days with a portable multifunctional device (Ray Magnetic DZB-718, INESA Scientific Instrument Co. Ltd., Shanghai, China) through observation tubes (Figure 1). The observation tubes were plugged into the 0–10 and 10–20 cm soil layers. The bottom of the observation tube was sealed, and the filters communicated to the observation tube and soil layer. Soil cores were taken from the 0–10 and 10–20 cm soil layers separately with three replicates in each container after 15 days. The ARS was measured by the active reducing substance volumetric method (Wang et al. 2017b). Repeated measures ANOVA was used to study the influence of straw return and aeration on

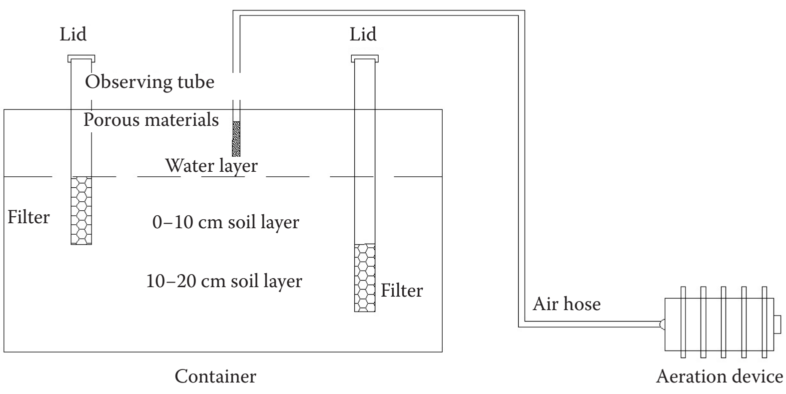

Figure 1. Schematic drawing of observing tubes and aeration device

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DO and ORP. Differences in ARS among treatments were analyzed using a post hoc test with LSD in SPSS software version 17.0.

RESULTS AND DISCUSSION

Influence of straw return and aeration on dissolved oxygen dynamics. The DO in all treatments showed a downward fluctuating trend (Figure 2). According to the results in Table 1, there were interactions between treatment and time in the 0–10 and 10–20 cm soil layer. Straw return caused a significant decrease in DO in the water layer (from 3 to 15 days of incubation), 0–10 cm soil layer (from 3 to 9 days) and 10–20 cm soil layer (from 3 to 6 days) ($P < 0.05$) (Table 2). Compared to the NS treatment, the DO in the S treatment was reduced by 44.04%, 58.11% and 23.02% on average in the three layers, respectively. Kögel-Knabner et al. (2010) reported that the labile organic carbon compounds contained in straw pieces could increase soil microbial activity and respiration. Therefore, the decreased DO could be attributed to strengthened soil respiration.

Aeration treatments significantly improved the DO in the water layer and in the 0–10 cm soil layer ($P < 0.05$) (Table 2). The enhancement weakened over time and with soil depth (Figure 2), which was probably due to the lower oxygen diffusion rate in the soil layers. In contrast to the S treatment, the DO in the SO_{30} treatment increased by 41.03%, 58.12% and 24.91% on average in the three layers, respectively, while the DO in the SO_{90} treatment was further promoted due to the increased duration of aeration, with mean increases of 105.47%, 119.94% and 41.73%, respectively. Zhu et al. (2019) obtained a similar result: aerated irrigation using a "Mazzei" venturi air injector significantly increased soil oxygen concentrations by 16% compared to normal irrigation in a greenhouse experiment.

Influence of straw return and aeration on redox potential. The ORP in all treatments showed a remarkable decline in the first few days and then levelled off (Figure 3). According to the results in Table 3, there were interactions between treatment and time in the three layers. Straw return to flooded soils caused the ORP to decline faster and ultimately resulted in the lowest value, with average decreases of 52.85, 48.82 and 47.24 mV in the three layers, respectively, with respect to the NS treatment (Table 4). The differences between the NS and S treat-

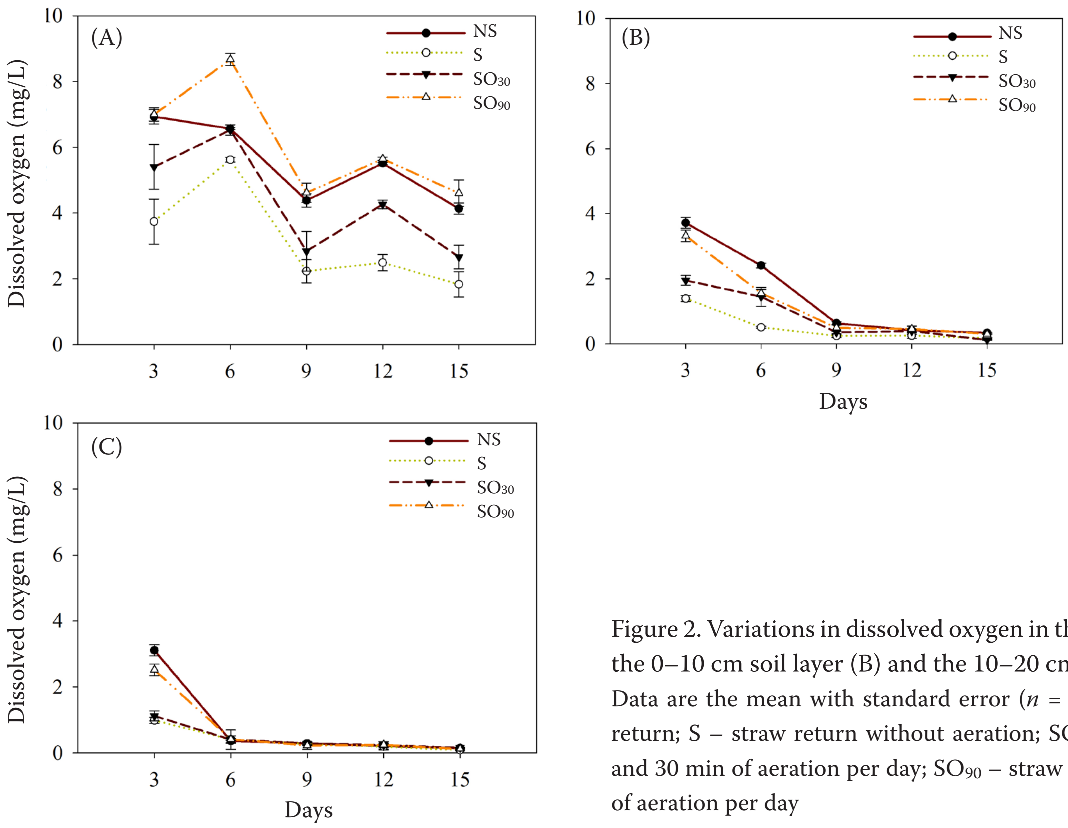

Figure 2. Variations in dissolved oxygen in the water layer (A), the 0–10 cm soil layer (B) and the 10–20 cm soil layer (C)
Data are the mean with standard error (n = 3); NS – no straw return; S – straw return without aeration; SO_{30} – straw return and 30 min of aeration per day; SO_{90} – straw return and 90 min of aeration per day

https://doi.org/10.17221/87/2020-SWR

Table 1. Results of repeated-measures ANOVA for dissolved oxygen in the three layers

Layer	Source	Sum of squares	df	Mean square	*F*-value	*P*-value
Water layer	time	109.31	2.08	52.49	96.22	< 0.05
	time × treatment	7.25	6.25	1.16	2.13	0.103
	error (time)	9.09	16.66	0.55		
0–10 cm soil layer	time	48.73	4.00	12.18	381.79	< 0.05
	time × treatment	8.38	12.00	0.70	21.89	< 0.05
	error(time)	1.02	32.00	0.03		
10–20 cm soil layer	time	27.53	4.00	6.88	149.26	< 0.05
	time × treatment	7.88	12.00	0.66	14.23	< 0.05
	error (time)	1.48	32.00	0.05		

df – degree of freedom

ments were significant in the water layer (from 3 to 15 days), 0–10 cm soil layer (from 3 to 6 days and 9 to 15 days) and 10–20 cm soil layer (from 3 to 6 days). The decomposition of straw consumed oxygen and triggered microbial activity to transform more redox species, leading to a lower ORP. The results agreed with related research conducted by Wang et al. (2012), in which wheat straw incorporation (6.5 t/ha) reduced the ORP in topsoil by 1.0–47.0 mV in a paddy field.

Aeration could promote ORP in the water and soil layers, while the enhancement of ORP in the soil layers was not as good as that in the water layer. In contrast to the S treatment, the ORP in the SO_{30} treatment increased by 25.29, 11.40 and 11.04 mV in the three layers, respectively, while in the SO_{90} treatment, it increased by 86.14, 35.51 and 40.28 mV, respectively (Table 4). O_2/H_2O was the principal redox couple, and the aeration system alleviated the reducing environment by supplying oxygen. Hu et al. (2017) obtained similar results: the ORP in the 10 cm soil layer was increased by 51.1–78.1 mV in a rice experimental plot after microbubble-aerated water irrigation.

Influence of straw return and aeration on active reducing substances. As shown in Table 5, straw return significantly increased the ARS in the soil layers ($P < 0.05$), with an average increase of 21.13–33.33% compared to the NS treatment. As mentioned above, straw return further aggravated hypoxia and amplified the reducing conditions, which

Table 2. Dissolved oxygen (DO) from different treatments in the three layers (the data listed in the table are the average with standard error)

Layer	Treatment	DO (mg/L)				
		day 3	day 6	day 9	day 12	day 15
Water layer	NS	6.93 ± 0.22^a	6.57 ± 0.03^b	4.38 ± 0.20^a	5.51 ± 0.03^a	4.14 ± 0.17^a
	S	3.74 ± 0.69^b	5.62 ± 0.07^c	2.23 ± 0.35^b	2.49 ± 0.25^c	1.83 ± 0.39^b
	SO_{30}	5.41 ± 0.68^a	6.53 ± 0.15^b	2.84 ± 0.60^b	4.26 ± 0.13^b	2.67 ± 0.36^b
	SO_{90}	7.00 ± 0.20^a	8.67 ± 0.18^a	4.62 ± 0.30^a	5.65 ± 0.05^a	4.61 ± 0.40^a
0–10 cm soil layer	NS	3.72 ± 0.17^a	2.41 ± 0.08^a	0.63 ± 0.05^a	0.42 ± 0.13^a	0.34 ± 0.02^a
	S	1.39 ± 0.09^c	0.51 ± 0.03^c	0.24 ± 0.04^b	0.25 ± 0.08^a	0.18 ± 0.02^b
	SO_{30}	1.95 ± 0.15^b	1.45 ± 0.29^b	0.35 ± 0.03^a	0.39 ± 0.05^a	0.12 ± 0.01^b
	SO_{90}	3.32 ± 0.18^a	1.56 ± 0.11^b	0.49 ± 0.11^a	0.46 ± 0.09^a	0.31 ± 0.02^a
10–20 cm soil layer	NS	3.11 ± 0.17^a	0.37 ± 0.08^a	0.29 ± 0.05^a	0.22 ± 0.13^a	0.15 ± 0.02^a
	S	0.99 ± 0.09^b	0.41 ± 0.03^a	0.27 ± 0.04^a	0.19 ± 0.08^a	0.09 ± 0.02^a
	SO_{30}	1.12 ± 0.15^b	0.41 ± 0.29^a	0.29 ± 0.03^a	0.24 ± 0.05^a	0.16 ± 0.01^a
	SO_{90}	2.52 ± 0.18^a	0.42 ± 0.11^a	0.23 ± 0.11^a	0.25 ± 0.09^a	0.12 ± 0.02^a

Different letters indicate significant differences between treatments ($P < 0.05$); NS – no straw return; S – straw return without aeration; SO_{30} – straw return and 30 min of aeration per day; SO_{90} – straw return and 90 min of aeration per day

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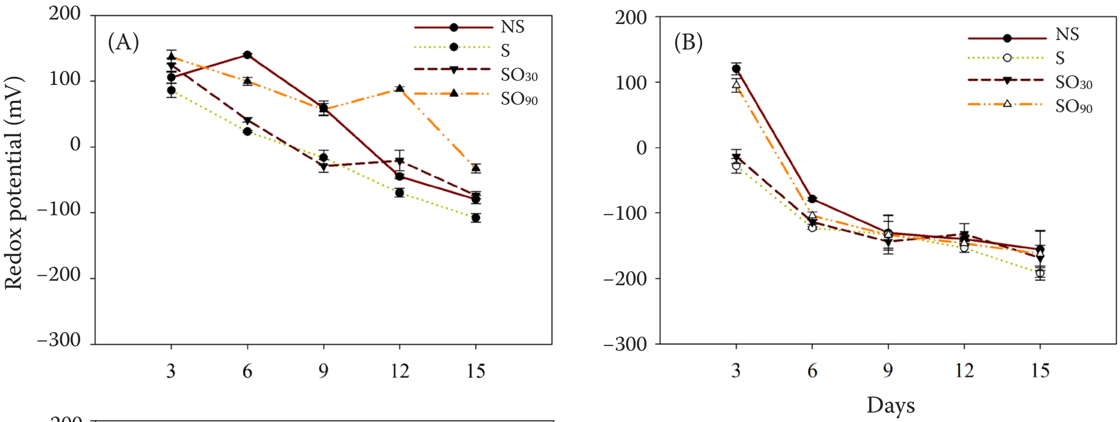

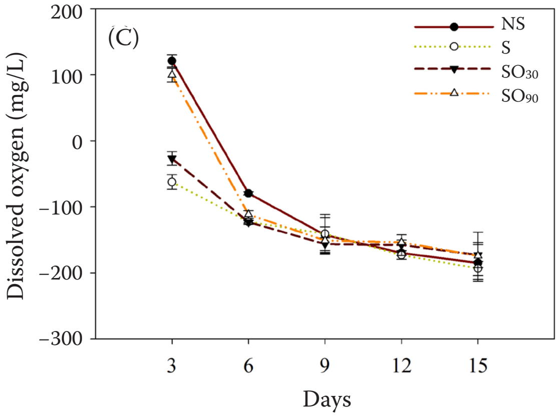

Figure 3. Variations in the redox potential in the water layer (A), the 0–10 cm soil layer (B) and the 10–20 cm soil layer (C)
Data are the mean with standard error (n = 3); NS – no straw return; S – straw return without aeration; SO_{30} – straw return and 30 min of aeration per day; SO_{90} – straw return and 90 min of aeration per day

was conducive to producing reducing substances. In general, molecular oxygen acts as the preferred electron acceptor during biological respiration. As the oxygen in flooded soil was gradually exhausted, the electron acceptor was switched from molecular oxygen to other substances, such as Mn^{4+}, Fe^{3+}, and SO_4^{2-}, accompanied by the formation of various reducing substances (Yuan et al. 2014).

In the present study, aeration reduced the amount of ARS by 5.32–12.04% in SO_{30} and 4.61–15.74% in SO_{90} in the soil layers compared to the S treatment (P < 0.05) (Table 5). Aeration for 90 min per day reached a better performance due to the increased oxygen supplementation. A significant difference existed only between the S and SO_{90} treatments in the 0–10 cm soil layer (P < 0.05). Overall, aeration has good prospects for application in paddies. Under most conditions, flooded soils become anoxic fairly quickly. Wetland plants, including paddy rice, generally have anatomical and physiological characteristics that allow them to cope with the challenging physicochemical conditions in the rhizosphere, but

Table 3. Results of repeated-measures ANOVA for redox potential in the three layers

Layer	Source	Sum of squares	df	Mean square	F-value	P-value
Water layer	time	257 677.34	2.37	108 618.32	301.57	< 0.05
	time × treatment	39 985.21	7.12	5 618.30	15.60	< 0.05
	error (time)	6 835.61	18.98	360.18		
0–10 cm soil layer	time	341 857.65	2.32	147 332.73	196.96	< 0.05
	time × treatment	34 983.89	6.96	5 025.75	6.72	< 0.05
	error(time)	13 885.35	18.56	748.03		
10–20 cm soil layer	time	356 990.86	4.00	89 247.72	203.06	< 0.05
	time × treatment	57 055.87	12.00	4 754.66	10.82	< 0.05
	error (time)	14 064.75	32.00	439.52		

df – degree of freedom

https://doi.org/10.17221/87/2020-SWR

Table 4. Redox potential (ORP) from different treatments in the three layers (the data listed in the table are the average with standard error)

Layer	Treatment	ORP (mV)				
		day 3	day 6	day 9	day 12	day 15
Water layer	NS	105.87 ± 9.23[b]	139.77 ± 2.38[a]	59.46 ± 10.48[a]	–44.79 ± 3.61[c]	–79.51 ± 6.38[b]
	S	86.14 ± 11.14[b]	23.55 ± 1.75[d]	–15.95 ± 11.03[b]	–69.41 ± 6.41[c]	–107.76 ± 6.68[c]
	SO_{30}	124.5 ± 10.6[b]	41.21 ± 3.32[c]	–28.69 ± 9.6[b]	–20.66 ± 15.58[b]	–73.36 ± 5.62[b]
	SO_{90}	136.69 ± 10.42[a]	100.08 ± 5.83[b]	57.02 ± 9.25[a]	88.23 ± 3.42[a]	–32.51 ± 6.63[a]
0–10 cm soil layer	NS	120.33 ± 9.23[a]	–78.85 ± 2.38[a]	–130.32 ± 26.33[a]	–139.75 ± 3.61[a]	–155.75 ± 27.72[a]
	S	–27.9 ± 11.14[b]	–122.8 ± 1.75[b]	–132.68 ± 29.49[a]	–153.34 ± 6.41[a]	–191.71 ± 10.69[b]
	SO_{30}	–13.53 ± 10.6[b]	–113.85 ± 3.32[b]	–143.76 ± 9.6[a]	–131.94 ± 15.58[a]	–168.37 ± 19.16[a]
	SO_{90}	95 ± 10.42[a]	–103.98 ± 5.83[b]	–133.41 ± 20.65[a]	–146.18 ± 3.42[a]	–162.3 ± 35.86[a]
10–20 cm soil layer	NS	120.99 ± 9.23[a]	–79.64 ± 2.38[a]	–142.54 ± 26.33[a]	–169.86 ± 3.61[a]	–184.92 ± 27.72[a]
	S	–62.22 ± 11.14[b]	–122.72 ± 1.75[b]	–140.89 ± 29.49[a]	–173.02 ± 6.41[a]	–193.31 ± 10.69[a]
	SO_{30}	–26.63 ± 10.6[b]	–123.16 ± 3.32[b]	–156.34 ± 9.6[a]	–157.86 ± 15.58[a]	–172.97 ± 19.16[a]
	SO_{90}	99.65 ± 10.42[a]	–111.54 ± 5.83[b]	–150.84 ± 20.65[a]	–153.78 ± 3.42[a]	–174.24 ± 35.86[a]

Different letters indicate significant differences between treatments ($P < 0.05$); NS – no straw return; S – straw return without aeration; SO_{30} – straw return and 30 min of aeration per day; SO_{90} – straw return and 90 min of aeration per day

this ability is limited during the germination and seedling stages. Aeration devices can help improve the rhizosphere environment by supplying oxygen. Minamikawa and Makino (2020) reported oxygen NB water could be used to control the redox conditions in various aquatic environments, including flooded paddy soils. Based on the experiment, the controlled area of one aeration device was approximately 2 m^2 (10 cm water depth), and 90 min of aeration per day could maintain the water quality in 7 days. With the development of more effective aeration devices with abundant nanobubbles, the hypoxia and reducing conditions caused by straw return could be alleviated for a longer time and at a larger spatial scale. Furthermore, other factors, such as energy use, agricultural productivity and environmental benefits, should also be synthetically considered in future work.

Table 5. Active reducing substances (ARS) from different treatments after 15 days in the soil layers (the data listed in the table are the average with standard error)

Soil layer (cm)	ARS (cmol/kg)			
	NS	S	SO_{30}	SO_{90}
0–10	1.57 ± 0.09[a]	2.29 ± 0.08[c]	2.1 ± 0.05[bc]	1.93 ± 0.02[b]
10–20	1.63 ± 0.04[a]	1.97 ± 0.03[b]	1.87 ± 0.04[b]	1.82 ± 0.03[b]

Different letters above the bars indicate significant differences between treatments ($P < 0.05$); NS – no straw return; S – straw return without aeration; SO_{30} – straw return and 30 min of aeration per day; SO_{90} – straw return and 90 min of aeration per day

CONCLUSION

The experiment showed that (1) straw return in paddy fields poses potential risks in deteriorating the soil environment for plant growth by exacerbating hypoxia and reducing conditions in the soil. (2) Aeration could alleviate the negative impact of straw return by supplying oxygen, but the effects weakened over time and with soil depth. Based on the experiment, aeration for 90 min per day with straw return could significantly improve the aerobic and redox conditions in the water layer and the 0–10 cm soil layer ($P < 0.05$). Further research is still needed to accurately determine the oxygen supply rates and improve aeration device working efficiency.

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