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Direct Application of Fresh Spent Mushroom Substrates Enhances Rice Grain Yields

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ABSTRACT: Spent mushroom substrate (SMS), the residual byproduct of mushroom cultivation, represents a nutrient-rich agro-residues with potential for paddy field application. This study evaluated the effect of direct SMS application on rice yield, yield components, biomass production, and nitrogen uptake (NU), aiming to provide useful information for fresh SMS utilization in paddy. Field experiments were conducted using a split-plot design with three replications, three SMS rates (0, 9, and 18 t ha^{-1} dry matter) as the main plots and three nitrogen (N) (0, 90, 180 kg ha^{-1}) as subplots in 2023 and 2024. Each plot was planted with rice cultivars Jingliangyou-534 (2023–2024) and Yongyou-1540 (2024). Results indicated that SMS application (9 and 18 t ha^{-1}) significantly increased nitrogen content in straw and grain at maturity by 8.54%–41.42% and 1.71%–16.27%, respectively. Correspondingly, NU in straw, grain, and aboveground increased by 11.85%–92.81%, 11.22%–43.59%, and 11.28%–53.18%, respectively. Aboveground biomass, panicles per m^2 and spikelets per panicle increased by 6.83%–27.66%, 0.44%–24.54%, and 5.01%–13.26%, respectively; no consistent effects were observed on setting rate for either cultivar across both years. Grain yield improved by 4.70%–23.57%, compared with no SMS application. These findings provide preliminary evidence that fresh SMS (≤18 t ha^{-1} dry matters) can be applied directly, without composting, as a convenient and effective strategy to enhance rice productivity, though further studies are needed to clarify the mechanisms underlying increased N uptake.

KEYWORDS: Spent mushroom substrate; direct application; rice; yield; nitrogen uptake

1 Introduction

Rice, as China's staple crop, is vital for national food security [1,2]. Its production largely depends on soil fertility and nutrient availability, traditionally maintained through chemical fertilizers [3]. However, excessive fertilizer use can degrade soil physicochemical properties and reduce crop performance [4]. Integrating organic fertilizers has proven effective for nutrient supply and soil organic matter accumulation, with the long-term combined organic-chemical fertilization can stabilize crop yield [4,5].

The edible mushroom industry in China has expanded rapidly, with production enterprises and output increasing steadily. Consequently, the accumulation of spent mushroom substrates (SMS) is substantial; China accounts for over 75% of global edible mushroom production [6]. SMS, the residual agro-residue from mushroom cultivation, is rich in organic matter and nutrients, including nitrogen, phosphorus, and potassium [7]. Approximately 5 kg of SMS is produced per kilogram of harvested mushrooms [8]. Traditionally discarded, SMS poses environmental and resource challenges [9], prompting exploration of reuse strategies. Among these, agricultural application is both economically and ecologically viable [10,11].

The use of compost as a soil amendment is both environmentally and economically viable [12]. Spent mushroom compost (SMC) is a product of SMS composting, which enriches soil with organic matter, enhancing soil water and nutrient retention and improving soil structure [13]. Its application can significantly increase soil mineral nitrogen, with synergistic effects when combined with urea [10]. Similarly, integrating SMC into rice cultivation improves seedlings' quality and vigor, promotes root development, and enhances the activity and abundance of beneficial microorganisms [6,14]. Rice seedlings grown in substrates containing SMC exhibit faster recovery after transplanting, and potentially higher tiller numbers [15]. Dar et al. [9] demonstrated that SMC with a low C:N ratio boosts grain and straw yield as well as total dry matter production, whereas high C:N ratios can reduce these parameters.

However, the nutrients in SMS are not immediately available to plants, necessitating composting prior to application [10,14]. Research on the direct use of fresh SMS in paddy soils remains limited. In this study, we evaluated fresh SMS derived from Pleurotus geesteranus, a widely cultivated mushroom in southern China [14]. The substrates were applied directly, without fermentation, in two field experiments with three SMS rates across three nitrogen levels during 2023 and 2024 in Xingyi City, Guizhou Province, China. The objective was to assess the effects of direct SMS application on grain yield, yield components, biomass production, and nitrogen uptake in rice.

2 Materials and Methods

2.1 Experimental Site, Soil, Spent Mushroom Substrates and Rice Cultivar

Field experiments were conducted in Xingyi City (25°01′14″ N, 104°55′45″ E, 1170 m asl), Guizhou Province, China, during 2023 and 2024. After harvesting pleurous geesteranus mushrooms in the same year as the experiment, the SMS was sun-dried and applied prior to rice transplanting in both years. The SMS were acquired from a nearby edible mushroom company. Soil samples (0–20 cm layer) were collected prior to transplanting in 2023. The chemical characteristics of the soil and SMS are presented in Table 1.

Table 1: Chemical characteristics of soil and spent mushroom substrates used in the experiment.

Chemical Characteristics	Soil	Spent Mushroom Substrates
pH	7.18 ± 0.02	8.61 ± 0.02
Organic matter (g kg^{-1})	60.09 ± 0.16	254.48 ± 1.59
Total nitrogen (g kg^{-1})	2.80 ± 0.05	11.96 ± 0.25
Total phosphorus (g kg^{-1})	1.40 ± 0.002	0.41 ± 0.002
Total potassium (g kg^{-1})	10.10 ± 0.06	9.60 ± 0.17
Available nitrogen (mg kg^{-1})	245.67 ± 5.52	872.00 ± 8.33
Available phosphorus (mg kg^{-1})	21.10 ± 1.47	262.20 ± 13.02
Available potassium (mg kg^{-1})	284.67 ± 8.21	3888.26 ± 205.85

In 2023, the hybrid rice cultivar Jingliangyou-534 (Production date: 2022.09) was used. In 2024, two hybrid cultivars, Jingliangyou-534 (Production date: 2023.09) and Yongyou-1540 (Production date: 2023.10), were evaluated. Both cultivars are high-yielding and well-adapted to Xingyi City conditions, and purchased from the local agricultural market in the year of the experiment. The basic properties of the cultivars were shown in Table 2.

Table 2: Basic properties of rice cultivars used in the experiments.

Cultivars	Year of Release	Female Parent	Male Parent	Plant Height (cm)	Growth Period (d)	Breeding Institution
Jingliangyou-534	2019	R534	Jing4155S	113.8	146.1	Yuan Longping Agricultural High-tech Co., Ltd.
Yongyou-1540	2015	F7540	Yongjing15A	105.8	151.0	Ningbo Seed Industry Co., Ltd.

Data source: China Rice Data Center (https://www.ricedata.cn/).

2.2 Experimental Design and Crop Management

The experiments were arranged in a split-plot design, with SMS rate (dry matter) as the main plots and the nitrogen (N) rate as subplots with three replicates per treatment in 2023 and 2024 (Table 3). Rice seedlings (25 days old) were manually transplanted on 03 May, with two seedlings per hill and a spacing of 20 cm × 26.7 cm in both years.

Table 3: Experimental design in 2023 and 2024.

Year	Main Plot SMS Rate (Dry Matter t ha^{-1})			Subplot N Rate (kg ha^{-1})			Sub-Subplot Cultivar		Plot Size (m^2)
	S0	S1	S2	N0	N1	N2			
2023	0	9	18	0	90	180	Jingliangyou-534		30
2024	0	9	18	0	90	180	Jingliangyou-534	Yongyou-1540	15

Note: SMS and N are represented the spent mushroom substrates and nitrogen, respectively.

Three SMS rates were tested: 0 (S0), 9 (S1), and 18 t ha^{-1} dry matter (S2), applied 1 day before transplanting. Nitrogen was applied at 0 (N0), 90 (N90), and 180 kg ha^{-1} (N180) in three splits: 50% as basal one day before transplanting, 20% at 7 days after transplanting (tillering stage), and 30% at panicle initiation (earing stage). Phosphorus (P_2O_5) and potassium (K_2O) were applied at 60 and 120 kg ha^{-1}, respectively; P was applied as basal, while Kwas split equally between basal and earing stages.

2.3 Sampling and Measurements

Solar radiation and mean temperatures during the period from transplanting to maturity were recorded using an automatic weather station (Vantage Pro2, Davis Instruments Crop., Hayward, CA, USA) near the experimental field.

At maturity five hills per plot were hand-harvested, and panicle number was counted. Filled and unfilled spikelets were separated by submersion in tap water, and three 30 g subsamples of filled spikelets were counted manually. All plant organs were oven-dried at 70°C to constant weight to determine biomass and N content. The N was analyzed using a Skalar SAN Plus segmented flow analyzer. Yield components including spikelets per panicle (SPP), seed setting rate (SSR), grain weight (GW), and panicles per m^2 (PP), aboveground biomass, harvest index (filled grain biomass/aboveground biomass), and aboveground nitrogen uptake (NU per m^2 in different organs) were calculated.

Grain yield was determined from a 5 m^2 area per plot and adjusted to 13.5% moisture content.

2.4 Statistical Analysis

Data were analyzed separately by cultivar and year. Analysis of variance (ANOVA) was performed using an analytical software Statistix 8.0 (Tallahassee, FL, USA), and treatment means were compared using the least significant difference (LSD) test at $p < 0.05$.

3 Results

3.1 Temperature and Solar Radiation

The average daily temperature from transplanting to maturity was 22.63°C in 2023 and 22.73°C in 2024. Total incident solar radiation was 2112.06 MJ m^{-2} in 2023 and 1958.88 MJ m^{-2} in 2024, (Fig. 1).
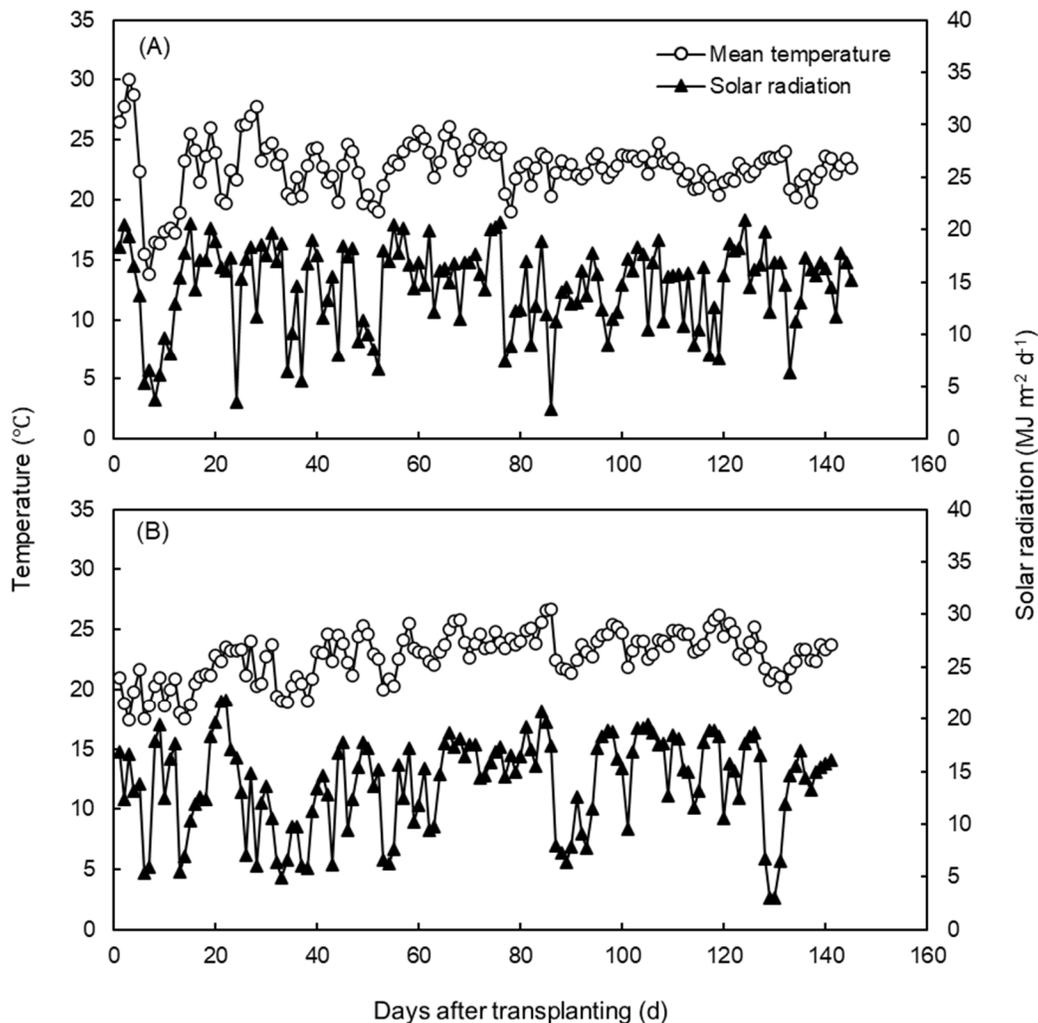

Figure 1: Daily mean temperature and solar radiation in 2023 (**A**) and 2024 (**B**).

3.2 Grain Yield and Yield Components

Grain yield was significantly affected by both nitrogen and SMS rates (Fig. 2). The application of nitrogen significantly increased grain yield, and SMS application also had a significant positive impact. Averaged across three nitrogen rates, grain yields under S1 and S2 were 12.05% and 18.69% higher in 2023 (Fig. 2A) and 4.70% and 10.09% higher in 2024 (Fig. 2B) with Jingliangyou-534, compared with S0. For

Yongyou-1540 in 2024 (Fig. 2C), S1 and S2 increased grain yield by 10.99% and 23.57%, respectively. The grain yield had a positive linear correlation with SMS rate for both cultivars in two years.
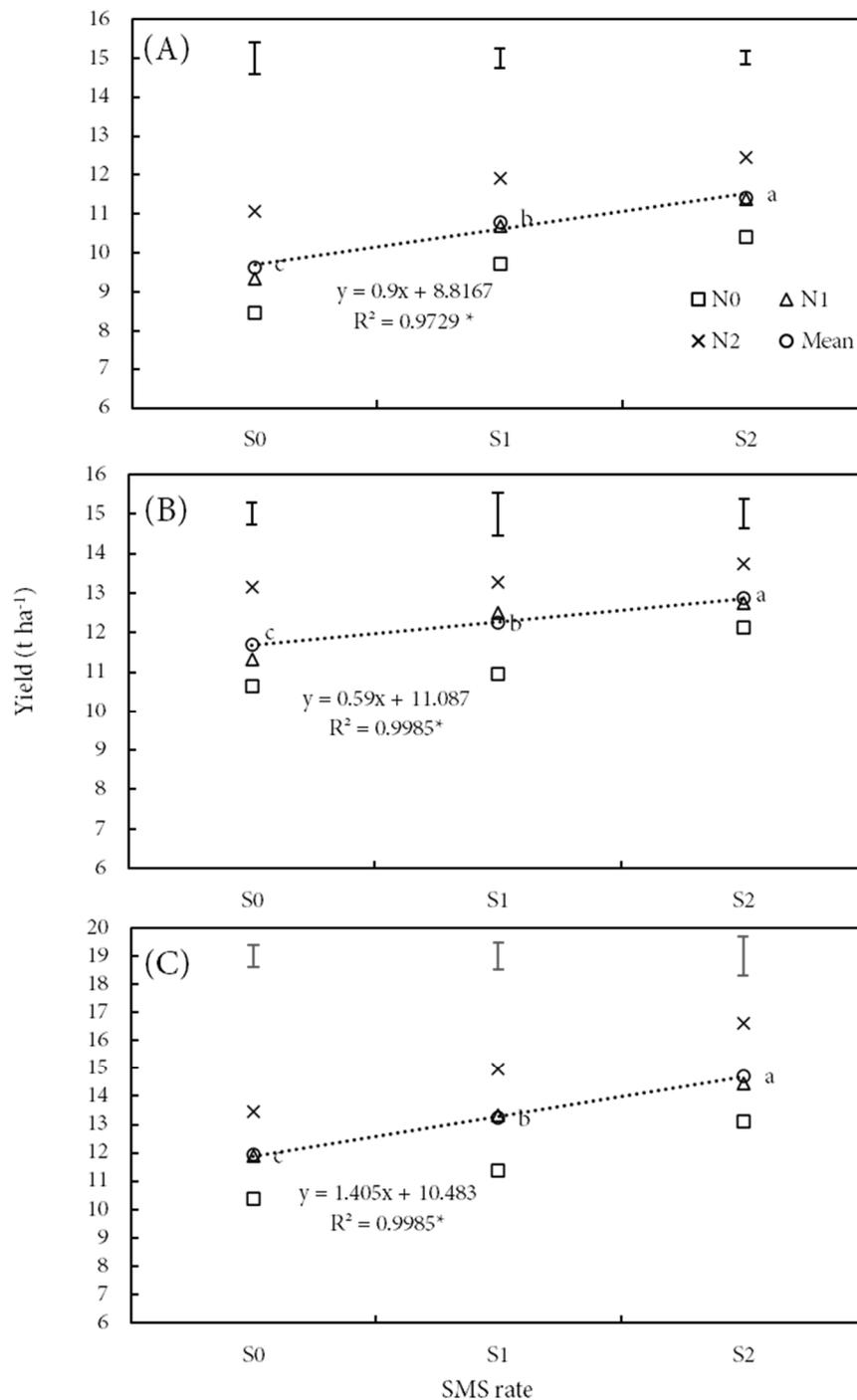
Figure 2: Effects of SMS application on yield of Jingliangyou-534 (**A**,**B**) and Yongyou-1540 (**C**) under three N rates in 2023 (**A**) and 2024 (**B**,**C**). Means followed by the different letters showed the differences are significant at the 0.05 probability level. Error bars are for the comparison of N rates at each SMS rate. Trend line showed the yield change followed by the SMS rate, *represent significance at the 0.05 probability level.

SMS application also significantly increased PP and SPP (Tables 4 and 5). In 2023 and 2024, S1 and S2 increased PP by 11.03% and 18.20%, and 16.92% and 24.54%, respectively, with Jingliangyou-534 (Table 4). For Yongyou-1540, S1 and S2 increased PP by 0.44% and 14.73%, though the difference between S1 and S0 was not significant. SPP increased by 7.05% and 8.07% in Jingliangyou-534 in 2023, and by 5.47% and 5.01% in Jingliangyou-534 and 11.27% and 13.26% in Yongyou-1540 in 2024. Average grain weight tended to decrease with increasing SMS, though differences were not significant in 2023 with Jingliangyou-534. In 2024, S1 and S2 reduced GW by 1.46% and 2.33% in Jingliangyou-534 and 2.38% and 4.27% in Yngyou-1540, respectively, with significant differences. No consistent effects were observed on SSR for either cultivar across both years.

Table 4: Effects of SMS application on yield components of Jingliangyou-534 under three N rates in 2023 and 2024.

Year	SMS Rate	N Rate	Panicles Per m^2	Spikelets Per Panicle	Setting Rate (%)	Grain Weight (mg)
		N0	260.75	171.03	86.33	21.97
	S0	N90	261.09	194.05	85.14	21.69
		N180	280.31	185.68	84.53	21.62
		Mean	267.38c	183.59b	85.33b	21.76a
		N0	272.16	192.30	85.70	21.70
2023	S1	N90	283.73	200.60	83.28	21.61
		N180	334.70	196.71	84.75	20.82
		Mean	296.86b	196.54a	84.58b	21.71a
		N0	287.06	187.72	89.49	21.98
	S2	N90	306.50	193.03	88.53	21.64
		N180	354.56	214.46	80.68	21.51
		Mean	316.04a	198.40a	86.23a	21.49a
Analysis of variance (F-value)						
	S		19.92**	12.54**	8.32**	2.76
	N		22.93**	12.57**	45.50**	6.73**
	S*N		2.02	5.06**	28.93**	0.50
		N0	222.50	223.36	88.73	21.53
	S0	N90	238.75	218.02	89.88	22.20
		N180	277.50	211.77	88.55	21.87
		Mean	246.25c	217.72b	89.05a	21.87a
		N0	248.75	218.36	88.21	21.67
2024	S1	N90	305.00	236.56	88.09	21.70
		N180	310.00	234.00	89.42	21.29
		Mean	287.92b	229.64a	88.58a	21.55ab
		N0	297.50	233.26	86.95	21.45
	S2	N90	291.25	228.36	84.78	21.29
		N180	331.25	224.25	82.39	21.32
		Mean	306.67a	228.62a	84.71b	21.36b
Analysis of variance (F-value)						
	S		30.32**	5.58*	25.98**	4.87*
	N		19.91**	0.60	1.66	1.16
	S*N		2.83	2.91	3.95*	1.54

Note: Within a column for each SMS rate treatment, means followed by a common letter are not significantly different at the 0.05 probability level. * and **represent significance at the 0.05 and 0.01 probability levels, respectively. SMS is spent mushroom substrate. S0, S1 and S2 are spent mushroom substrate rates of 0, 9, 18 t ha^{-1} (dry matters), respectively. N0, N90, and N180 are N rates of 0, 90 and 180 kg ha^{-1}, respectively.

Table 5: Effects of SMS application on yield components of Yongyou-1540 under three N rates in 2024.

Year	SMS Rate	N Rate	Panicles Per m²	Spikelets Per Panicle	Setting Rate (%)	Grain Weight (mg)
2024	S0	N0	158.75	301.21	95.04	22.31
		N90	203.75	282.15	93.15	22.33
		N180	197.50	324.55	91.33	22.13
		Mean	186.67b	302.64b	93.17a	22.26a
	S1	N0	165.00	311.53	91.94	21.84
		N90	190.00	344.11	93.40	21.63
		N180	207.50	354.58	92.35	21.72
		Mean	187.50b	336.74a	92.56a	21.73b
	S2	N0	191.25	347.73	95.32	21.56
		N90	220.00	327.70	90.29	21.36
		N180	231.25	352.91	88.27	21.01
		Mean	214.17a	342.78a	91.30b	21.31c
Analysis of variance (F-value)						
	S		23.36**	55.30**	8.75**	23.54**
	N		44.13**	24.62**	28.44**	2.05
	S*N		1.42	9.97**	13.12**	0.71

Note: Within a column for each SMS rate treatment, means followed by a common letter are not significantly different at the 0.05 probability level. **represent significance at the 0.01 probability levels, respectively. SMS is spent mushroom substrate. S0, S1 and S2 are spent mushroom substrate rates of 0, 9, 18 t ha⁻¹ (dry matters), respectively. N0, N90, and N180 are N rates of 0, 90 and 180 kg ha⁻¹, respectively.

3.3 Biomass Production and Harvest Index

Mean total biomass production (TBP) differed significantly among SMS rates across nitrogen levels for both rice cultivars in 2023 and 2024 (Table 6). Across N rates, S1 and S2 increased total biomass by 13.12% and 25.01% in 2023, and 21.38% and 27.66% in 2024 for Jingliangyou-534 compared with S0. For Yongyou-1540 in 2024, S1 and S2 increased TBP by 6.83% and 17.88%, respectively. The harvest index did not show a consistent change among three SMS rates, the Jingliangyou-534 under S1 treatment showed no consistent trend across SMS rates; Jingliangyou-534 exhibited the highest harvest index under S1 in both years, whereas Yongyou-1540 achieved the highest under S2 in 2024.

Table 6: Effects of SMS application on total biomass production and harvest index of Jingliangyou-534 and Yongyou-1540 under three N rates in 2023 and 2024.

Cultivar	SMS Rate	N Rate	Total Biomass Production (g m⁻²) 2023	Harvest Index (%) 2023	Total Biomass Production (g m⁻²) 2024	Harvest Index (%) 2024
Jingliangyou-534	S0	N0	1488.10	56.81	1643.30	57.60
		N90	1646.00	56.78	1803.30	57.56
		N180	1680.50	56.53	1949.90	58.32
		Mean	1604.86c	56.71b	1798.83c	57.82a
	S1	N0	1621.60	59.98	1861.12	55.71
		N90	1741.69	58.76	2328.03	59.14
		N180	2082.73	55.72	2361.02	58.38
		Mean	1815.34b	58.15a	2183.39b	57.74a
	S2	N0	1861.51	56.93	2257.78	57.28
		N90	1996.70	56.80	2149.12	55.85
		N180	2160.42	57.31	2482.50	52.52
		Mean	2006.21a	57.01ab	2296.47a	55.22b

Table 6: *Cont.*

Cultivar	SMS Rate	N Rate	Total Biomass Production (g m^{-2}) 2023	Harvest Index (%)	Total Biomass Production (g m^{-2}) 2024	Harvest Index (%)
Analysis of variance (F-value)						
	S		92.28**	3.68*	93.76**	30.60**
	N		61.94**	3.16	40.69**	4.32*
	S*N		5.12**	3.60*	9.64**	19.57**
	S0	N0			1725.83	58.68
		N90			2011.02	59.43
		N180			2123.67	60.98
		Mean			1953.51c	59.70c
	S1	N0			1765.87	58.42
		N90			2148.90	61.43
Yongyou-1540		N180			2346.13	62.88
		Mean			2086.97b	60.91b
	S2	N0			2152.34	63.42
		N90			2240.67	62.06
		N180			2515.21	60.15
		Mean			2302.74a	61.88a
Analysis of variance (F-value)						
	S				52.87**	36.86**
	N				85.52**	10.85**
	S*N				4.03*	43.90**

Note: Within a column for each SMS rate treatment, means followed by a common letter are not significantly different at the 0.05 probability level. * and **represent significance at the 0.05 and 0.01 probability levels, respectively. SMS is spent mushroom substrate. S0, S1 and S2 are spent mushroom substrate rates of 0, 9, 18 t ha^{-1} (dry matters), respectively. N0, N90, and N180 are N rates of 0, 90 and 180 kg ha^{-1}, respectively.

3.4 Nitrogen Uptake by Rice

The SMS application significantly increased aboveground nitrogen content (NC) and nitrogen uptake (NU) in Jingliangyou-534 in 2023 and 2024, and in Yongyou-1540 in 2024. (Table 7 and Fig. 3). NC in straw increased by 29.48%–35.37% and 10.82%–41.42% for Jingliangyou-534 in 2023 and 2024, and by 8.54%–18.73% for Yongyou-1540 in 2024. Grain NC increased by 11.51%–12.93% and 10.14%–16.29% for Jingliangyou-534 in 2023 and 2024, and 1.71%–8.67% for Yongyou-1540 in 2024 (Table 7). Aboveground NU under S1 and S2 was 35.28%–53.18% higher for Jingliangyou-534, and 11.28%–32.10% higher for Yongyou-1540 compared with S0. Average NU in straw and grain was elevated under S1 and S2 by 47.34%–71.16% and 31.10%–43.59% in 2023 and 33.90%–92.81% and 34.49%–40.70% in 2024 for Jingliangyou-534, and by 11.85%–31.43% and 11.22%–31.43% for Yongyou-1540 in 2024 (Fig. 3).

Table 7: Effects of SMS rate on aboveground nitrogen content at maturity under three N rates in 2023 and 2024 for Jingliangyou-534 and Yongyou-1540.

Cultivar	SMS Rate	N Rate	Nitrogen Content (g kg^{-1})			
			2023		2024	
			Straw	Grain	Straw	Grain
	S0	N0	4.24	8.87	2.88	7.66
		N1	4.26	10.36	3.30	9.07
		N2	5.23	10.23	5.20	9.61
		Mean	4.58b	9.82b	3.79c	8.78c
	S1	N0	4.46	10.04	3.32	8.44
Jingliangyou-534		N1	5.79	10.87	3.61	9.49
		N2	7.53	12.37	5.66	11.07
		Mean	5.93a	10.95a	4.20b	9.67b
	S2	N0	5.01	10.00	3.83	8.93
		N1	6.02	10.81	5.53	10.16
		N2	7.57	12.03	6.73	11.54
		Mean	6.20a	11.09a	5.36a	10.21a
Analysis of variance (F-value)						
	S		11.52**	19.52**	31.22**	17.52**
	N		18.99**	36.60**	78.01**	48.31**
	S*N		1.53	2.56	2.38	0.92
	S0	N0			3.18	7.80
		N1			3.80	8.82
		N2			3.91	9.70
		Mean			3.63b	8.77b
	S1	N0			3.71	8.08
Yongyou-1540		N1			3.88	8.85
		N2			4.24	9.83
		Mean			3.94ab	8.92ab
	S2	N0			3.54	8.50
		N1			4.16	9.92
		N2			5.24	10.18
		Mean			4.31a	9.53a
Analysis of variance (F-value)						
	S				7.63**	4.48*
	N				15.92**	21.96**
	S*N				2.60	0.41

Note: Within a column for each SMS rate treatment, means followed by a common letter are not significantly different at the 0.05 probability level. * and **represent significance at the 0.05 and 0.01 probability levels, respectively. SMS is spent mushroom substrate. S0, S1 and S2 are spent mushroom substrate rates of 0, 9, 18 t ha^{-1} (dry matters), respectively. N0, N90, and N180 are N rates of 0, 90 and 180 kg ha^{-1}, respectively.
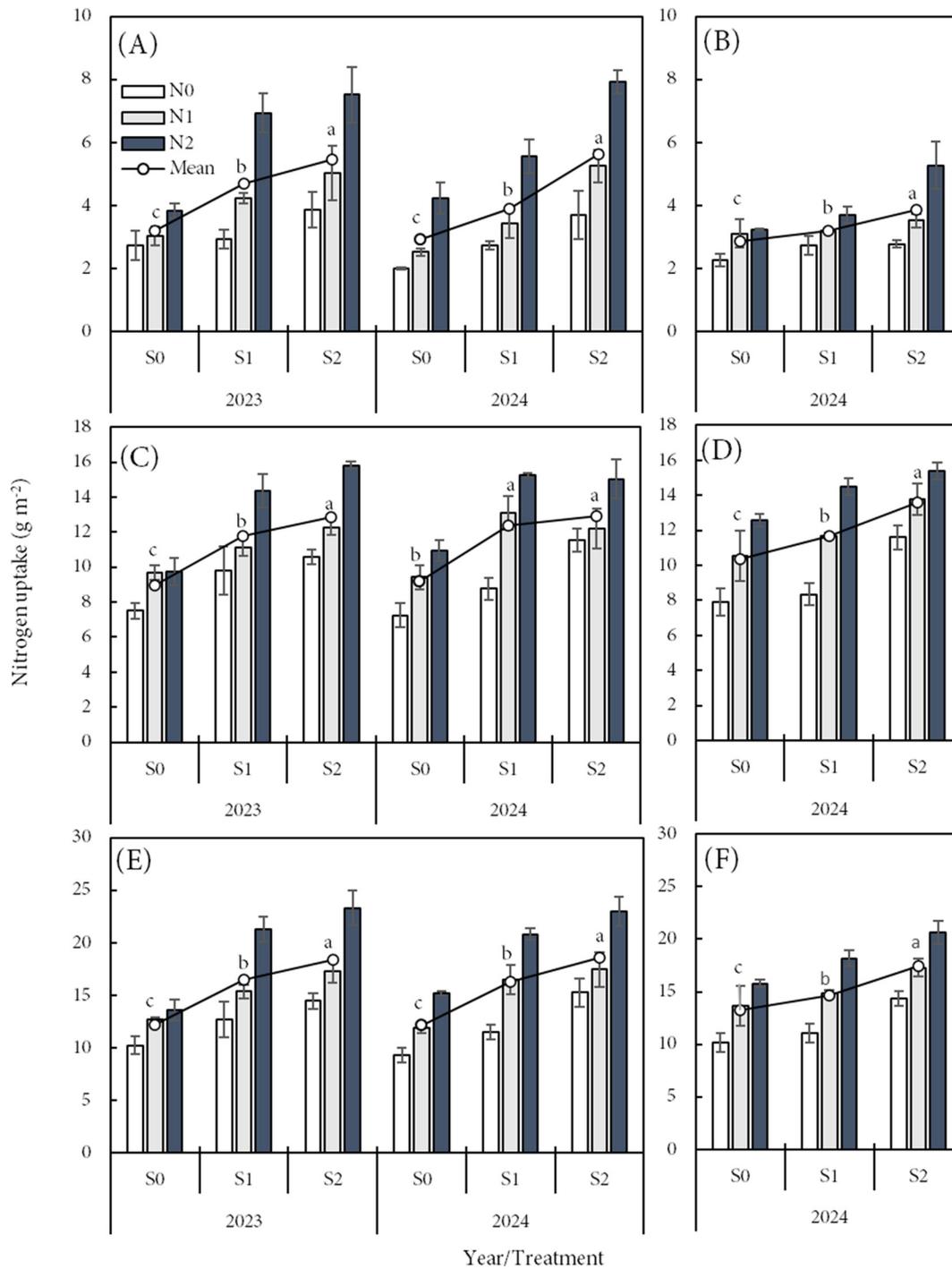
Figure 3: Effects of SMS rate on straw (**A**,**B**), grain (**C**,**D**) and aboveground (**E**,**F**) nitrogen uptake at maturity under three N rates in 2023 and 2024 for Jingliangyou-534 and Yongyou-1540. Different letters above the means showed the differences are significant at the 0.05 probability level.

4 Discussion

Previous research has demonstrated that SMC's advantageous qualities can improve rice's nutritional availability and uptake [14]. In comparison to no SMS application, the current study found that direct

SMS application without fermentation significantly increased NC in straw and grain by 8.54%−41.42% and 1.71%−16.27%, respectively, and improved NU in straw, grain and aboveground biomass by 11.85%−92.81%, 11.22%−43.59% and 11.28%−53.18%. These effects are probably caused by (1) the SMC had a low bulk density, loose texture, good air permeability, as well as the fact that it can be used to enhance the soil's physical structure [13,16]. Soils with a softer, looser texture are often more favorable for microbial colonization, this microbial presence plays an important role in nutrient cycling within the rhizosphere, facilitating the release and transformation of nutrients, thereby enhancing NU by plants [17]; and (2) SMS is rich in nutrients (higher organic matter, nitrogen, phosphorus, and potassium content) and enhanced mineral nitrogen availability, the available nitrogen in SMS directly supplements the nitrogen demand of rice [10], or the organic matter derived from SMS can increase microbial activity and soil porosity, thereby facilitating nutrient uptake [17]. The relative contributions of SMS, soil mineralization and applied N fertilizer to increased N uptake remain unclear and warrant further investigation.

Rice grain yield is influenced by TBP and harvest index, with a stronger correlation observed between yield and biomass compared to harvest index [18]. Organic fertilizers, which are rich in minerals, provide essential nutrients, that regulate plant growth [19]. In this study, the application of SMS resulted in an increase in TBP by 13.12%−27.66% for the Jingliangyou-534 and 6.83%−17.88% for the Yongyou-1540. These finding align with previous research indicating that the application of spent white button mushroom compost enhances TBP [9]. This improvement may be attributed to increased NU facilitated by SMS, which likely supports higher dry matter accumulation [20]. Furthermore, SMS application significantly affected PP and SPP. PP increased by 11.03%−24.54% for Jingliangyou-534 and 0.44%−14.73% for Yongyou-1540, while SPP increased by 5.01%−8.07% and 11.27%−13.26%, respectively. The enhanced seedling vigor and tillering capacity observed under SMC treatment may account for these increases [15]. The availability of nitrogen promotes cell division, thereby supporting higher tiller numbers and panicle density [21]. However, Mi et al. [22] reported no significant effect on SPP at lower SMS application rates combined with NPK, suggesting that the optimal SMS application rate and application period remains to be determined.

The long-term integration of organic and chemical fertilizers has been shown to stabilize crop yields [4]. SMC, rich in organic matter and nutrients [7], has been observed to increase grain yields by 4.70%−18.69% for Jingliangyou-534 and by 10.99%−23.57% for Yongyou-1540. These yield improvements are likely attributable to enhanced NU and biomass accumulation, aligning with previous studies on mushroom compost [9]. Similar finding indicated that SMS, when naturally weathered for 6 to 24 months or recomposted for 12 months, can enhance vegetative yield [23]. However, earlier research has demonstrated that due to the instability and immaturity of SMS, its use as a soil fertilizer is not yet well established [10,14,24]. SMC is considered the most efficient and economically viable method for recycling, as it provides stability and transforms this nutrient rich residue into a valuable product [24,25]. Nonetheless the composting process is complex, requiring specific equipment or facilities, and is influenced by temperature and moisture, resulting in a duration of 25 to 120 days, or longer [16,23,25−27]. Our finding suggested that the direct application of SMS without prior fermentation can effectively enhance NU, biomass, and grain yield, highlighting its practical potential as a convenient and time-saving agricultural amendment.

SMS exhibits a higher pH value, increased salt content, and reduced water holding capacity [28]. Its application to agroecosystems is regarded as a sustainable method for utilizing this product. However, potential hazards, such as the presence of pathogenic microorganisms and bacteria, must be considered [14,29]. Additionally, the SMC poses significant environmental risks due to the release of greenhouse gases during natural anaerobic digestion and the leachate drainage, which contaminates and eutrophicates water bodies, thereby depleting dissolved oxygen levels [28]. The instability of SMS renders

it unsuitable for storage, reduces the degree of organic matter biodegradation, and lead to the production of pathogens and phytotoxic compounds that could negatively affect plant development [24]. In our study, the direct application of fresh SMS was found to be beneficial for rice growth and yield. However, the potential risks associated with its direct application were not fully assessed. The SMS used in these experiments was the least product following mushrooms harvesting, applied prior to rice transplanting, which minimized nutrient loss. Nonetheless, the potential risks associated with the direct application of SMS warrant further investigation.

5 Conclusions

This study demonstrated that direct application of fresh SMS without prior fermentation in paddy fields significantly enhanced rice growth and productivity. Specifically, SMS increased aboveground NU, TBP, PP, and SPP, resulting in higher grain yields compared with untreated controls. These findings provide preliminary evidence that fresh SMS ($\leq$18 t ha^{-1} dry matter) can be applied directly as a practical and effective agricultural amendment to improve rice yield. Further research is needed to elucidate the relative contributions of SMS, soil mineralization, and fertilizer N to the observed increases in NU.

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