



The impact of varying straw return rates and nitrogen application timings on winter wheat performance and soil nutrient availability

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Abstract

Optimizing straw return and nitrogen (N) fertilizer management is critical for enhancing sustainable wheat production. A two-season field study investigated the synergistic effects of varying rice straw return rates (s_1 = full straw return, s_2 = 50% straw return, s_3 = no straw return) and split nitrogen fertilizer strategies (n_1 = conventional N, n_2 = 126 kg ha⁻¹ basal + 54 kg ha⁻¹ overwinter, n_3 = three-split N application; ck = control, no N fertilizer) on wheat yield, yield components, soil fertility, biomass accumulation, and photosynthetic efficiency. The results consistently demonstrated that the combined strategy had a significant impact on all measured parameters. The optimal treatment, 50% straw return (s_2) coupled with a two-split nitrogen application (n_2), maximized wheat grain yield at approximately 7,384±173 kg ha⁻¹, representing a 15–19% increase over conventional practices (s_3 - n_1). This yield advantage was primarily attributed to enhanced spike formation. Furthermore, full straw return (s_1) combined with a three-split nitrogen application (n_3) significantly improved soil fertility, achieving the highest soil organic carbon (SOC) content (22.1 g kg⁻¹), which was 55.1–81.5% higher than conventional methods, alongside substantial increases in soil N, P, and K. The s_2 - n_2 treatment also led to peak dry matter accumulation (31,604 kg ha⁻¹ at maturity), a 158% increase over the control (ck). For photosynthetic performance, 50% straw return (s_2) with three-split nitrogen (n_3) consistently produced superior SPAD values (83.1) and LAI (4.65) at 14 days after flowering, sustaining active photosynthesis 50–100% longer than conventional practices. These research findings underscore that moderate straw retention combined with strategic split nitrogen application provides a balanced approach, enhancing both wheat productivity and soil health by optimizing nutrient availability and prolonged photosynthetic activity, while avoiding the yield penalties associated with excessive incorporation.

Keywords: Straw return; nitrogen split application; yield; soil organic carbon; soil fertility; photosynthesis; biomass accumulation; sustainable agriculture

Introduction

Wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) rank as the second and third most crucial crops globally and in China, contributing significantly to the food supply and dietary energy. Wheat alone constitutes 26% of the global food supply and is a primary dietary staple for over one-third of the world's population (Rustgi *et al.*, 2019; Akwakwa and Xiaoyan, 2023). Rice feeds more than half of the global population (Fao, 2018). As a leading producer, China contributes 17% to the global wheat output, primarily through winter wheat varieties, which account for 95% of its national production (Song *et al.*, 2019). This agricultural prominence results in the production of over 700 million tons

of crop residues or "straw" annually, covering more than 24 million hectares (Wang *et al.*, 2023). However, sustainable management of this straw is challenging, as less than 40% is returned to the fields (Li *et al.*, 2018), and the prevalent practice of burning straw—although cost-effective—is environmentally unsustainable and has thus been prohibited (Bellamy *et al.*, 2005; Suriyagoda *et al.*, 2014).

Straw return, the practice of reincorporating crop residues into the soil, offers a promising agricultural strategy that not only mitigates pollution but also boosts crop yields and soil fertility (Lal, 2004; Akwakwa and Xiaoyan, 2023). Numerous studies confirm the benefits of straw return for enhancing subsequent crop performance and improving soil health (Berhane *et al.*, 2020). Research by Wu *et al.* (2022) and Chen MengYun *et*

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al.(2017) has shown that straw incorporation can significantly increase total plant biomass and improve photosynthetic efficiency, thereby enhancing yields. However, the impacts of straw return are not consistently positive; while some studies report beneficial outcomes (Huang *et al.*, 2017), others have noted negative (Yao *et al.*, 2017; Xu *et al.*, 2021) or negligible effects (Zhang *et al.*, 2017).

These effects are mediated by soil properties and nitrogen dynamics, where straw return combined with nitrogen fertilization enhances fertility while reducing environmental impacts (Bakht *et al.*, 2009; Han *et al.*, 2018). Inefficient nitrogen management can result in substantial losses due to leaching, runoff, and volatilization, potentially reducing crops yields by more than 40% (Zhang *et al.*, 2020). In rice-wheat systems, while the traditional approach involves applying all nitrogen fertilizer as a basal dose before planting, recent studies recommend a shift towards reduced basal and increased top-dressing applications to align more closely with crop needs—a practice now encouraged in countries like China, Japan, India, Australia, Italy, and Argentina (Melaj *et al.*, 2003; Ercoli *et al.*, 2013; Cao *et al.*, 2018; Jing Wang *et al.*, 2019; Berhane *et al.*, 2020; Wood *et al.*, 2021). However, under conditions where straw is returned, some researchers argue for an increase in basal nitrogen applications to counteract the immobilization effects of the returned straw (Cao *et al.*, 2018; Zheng *et al.*, 2019).

The interaction between straw return and nitrogen fertilization is complex and does not always produce positive results. In some cases, high basal nitrogen combined with low top-dressing can complement straw return, while in other scenarios, reduced basal nitrogen and increased top-dressing prove more beneficial. Despite these findings, the understanding of how different nitrogen top-dressing regimes influence the effects of straw return remains incomplete. This study seeks to clarify these interactions by evaluating the impact of straw return across varying nitrogen top-dressing strategies and offering practical recommendations for optimizing straw return under different fertilization regimes.

Materials and Methods

Experimental site description and planting material

The experiment was conducted during the growing seasons 2021-2022 and 2022-2023 at the Taihu experimental farm station of Yangtze University, Jingzhou, Hubei Province, China (30°03'N, 112°00'E). The monthly total rainfall and average temperature during the growing season are presented in (Figure 1). The soil at the site is classified as a calcareous alluvial soil with a sandy loam texture (Qiand Pan, 2022), and,

and the basic physical and chemical properties of the soil in the 0-20 cm soil layer before the experiment were as follows: organic matter, 23.39 g kg⁻¹; total nitrogen, 1.19 g kg⁻¹; nitrate nitrogen, 39.56 mg kg⁻¹; available phosphorus, 27.67 mg kg⁻¹; available potassium, 87.51 mg kg⁻¹; pH, 7.2. The wheat variety used for this experiment was Yangmai 23 (YM23), a variety cultivated high-yielding winter wheat variety in the middle and lower reaches of the Yangtze River region of China (Gao *et al.*, 2022; Akwakwa and Xiaoyan, 2023). The wheat seeds were provided by Jiangsu Golden Land Seed Industry Co., Ltd. (Jiangsu, China).

Experiment description

The experiment included two factors: rice straw return percentage and nitrogen topdressing management. Rice straw return was applied at three levels: S1 (100% straw return), S2 (50% straw return), and S3 (0% straw return). Four nitrogen topdressing regimes were tested: n1 (100% basal application), n2 (70% basal, 30% over-winter), n3 (equal split across basal, over-winter, and jointing stages), and ck (no nitrogen applied). The total nitrogen application rate for n1, n2, and n3 was 180 kg ha⁻¹. Phosphate and potash fertilizers were uniformly applied at rates of 105 kg ha⁻¹ K₂O and 105 kg ha⁻¹ P₂O at the time of planting for all treatments. The experimental design followed a randomized block arrangement with three replications per treatment. Each plot measured 20 m × 2 m (40 m²) with a 0.5 m gap between plots. Wheat seeds were sown at a density of 10.93 g m⁻². The experimental design and treatment combinations are detailed in Table 1.

Data collection

Yield and its components

Grain yield and its components were measured from two 2 m² harvest areas located in the middle of each plot. All wheat spikes were manually harvested, threshed, and weighed to determine the total grain yield. The average grain weight per spike was estimated by randomly selecting 30 spikes per plot. Yield data from the two harvest areas were then converted to kg ha⁻¹. Additionally, 1000 grains were randomly sampled from each plot and weighed to determine the 1000-grain weight. This process was repeated across the three replicate plots for each treatment.

Soil fertility characteristics

Soil samples were collected at 2 stages, flowering (FLW) and maturation stage (MAT), at a depth of 0-20 cm, following recommended procedures (Marschner *et al.*, 2011). In brief, five soil samples from each plot were obtained and mixed as a composite sample. The potassium dichromate oxidation process combined with the heating method was used to



measure the soil organic carbon (SOC). Available phosphorus (AP) was ascertained using the molybdenum antimony colorimetric method, and available potassium (AK) by the flame photometer method. Total nitrogen (TN) was determined using the Kjeldahl method. Total phosphorus (TP) was identified based on the sodium hydroxide melting-

molybdenum antimony colorimetric method (Gao *et al.*, 2022). All soil analyses were carried out in the soil chemistry laboratory of the College of Agriculture, Yangtze University. All analyses were carried out for the three independently replicated plots.

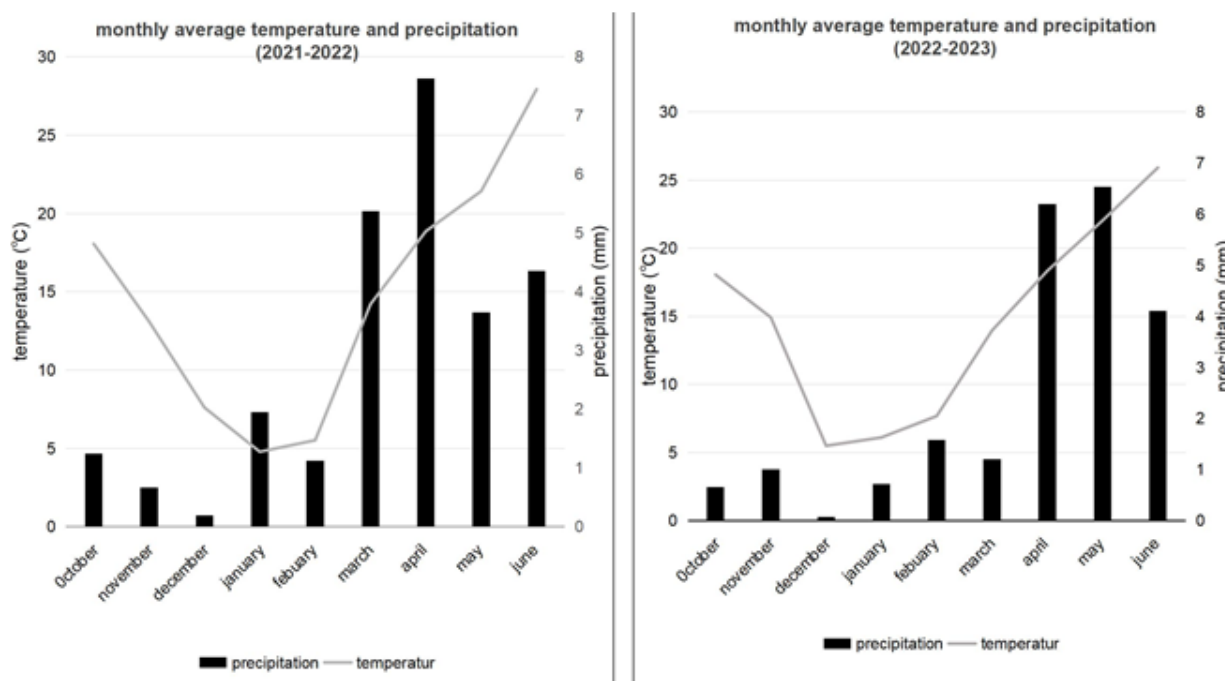


Figure 1: Monthly average temperature (°C) and precipitation (mm) during the wheat growing seasons

Table 1: Experimental design for wheat cultivation under different rice straw return and nitrogen management strategies

Rice straw return (straw)	Nitrogen topdressing (NTD)	Treatment name	Nitrogen application timing (kg ha ⁻¹)			
			Total (N)	Basal	Overwinter	jointing
s1 (100%)	n1 (1:0:0)	s1-n1	180	180	0	0
	n2 (7:3:0)	s1-n2	180	126	54	0
	n3 (1:1:1)	s1-n3	180	60	60	60
	ck (0:0:0)	s1-ck	0	0	0	0
s2(50%)	n1 (1:0:0)	s2-n1	180	180	0	0
	n2 (7:3:0)	s2-n2	180	126	54	0
	n3 (1:1:1)	s2-n3	180	60	60	60
	ck (0:0:0)	s2-ck	0	0	0	0
s3(0%)	n1 (1:0:0)	s3-n1	180	180	0	0
	n2 (7:3:0)	s3-n2	180	126	54	0
	n3 (1:1:1)	s3-n3	180	60	60	60
	ck (0:0:0)	s3-ck	0	0	0	0



Total biomass

Total biomass was collected at three key growth stages: flowering, 14 days after flowering, and at maturity. Fifteen plants were randomly selected from each plot, and the roots were separated from the above-ground portions. The total number of spikes per plant was counted. The plant samples were dehydrated by placing them in an oven at 105°C for 30

minutes, followed by drying to a constant weight at 70°C. The dry matter content of the stems was measured, and the total above-ground biomass for each plot was calculated using the following formula:

$$\text{Total biomass} = \frac{\text{weight of 15 plants}}{\text{number of spikes in 15 plants}} * \text{total spike number in the field}$$

Table 2: Effects of straw return rates and nitrogen application timings on wheat yield and yield components

Years	Straw	Nitrogen	GY (kg ha ⁻¹)	SP (10 ⁴ ha ⁻¹)	Grain/Spikes	TGW (g)
2021 -2022	s1	n1 (1:0:0)	6533.5±236bc	305.75±58cd	54±2c	38.5±0.4bc
		n2 (7:3:0)	7024.5±225ab	393.25±34ab	58±2abc	36.35±2cd
		n3 (1:1:1)	5313.5±714d	329.5±23bc	56.6±4abc	34.7±0.4d
		ck (0:0:0)	2019.75±79f	172.75±20ef	33±2f	31.45±0.8e
	s2	n1 (1:0:0)	6820.5±166ab	336±22bc	59±2abc	38.4±1bc
		n2 (7:3:0)	7383.5±173a	432±6a	61±2a	38.4±1bc
		n3 (1:1:1)	5839.5±72cd	311.25±2cd	57±2abc	37.05±1bcd
		ck (0:0:0)	2166.75±129f	185±49ef	42±2d	31.15±2e
	s3	n1 (1:0:0)	6807.5±290ab	340.5±44bc	58±2abc	41.95±0.8a
		n2 (7:3:0)	7121.25±678ab	417.5±3a	59.8±2ab	39.4±0.8ab
		n3 (1:1:1)	4309.75±185e	238±23de	55±3bc	38.35±1bc
		ck (0:0:0)	1503±146f	144±7f	41.7±2d	35.35±0.6d
2022 -2023	s1	n1 (1:0:0)	6206.8±224bc	290.5±55de	51.6±2c	36.6±0.4abc
		n2 (7:3:0)	6673.3±214ab	373.6±32abc	55.5±21abc	34.5±2.04bcd
		n3 (1:1:1)	5047.8±678d	313±22cd	53.7±3bc	32.9±0.3cde
		ck (0:0:0)	1918.8±75e	164.1±19f	31.3±2e	29.9±0.8de
	s2	n1 (1:0:0)	6479.5±158b	331.8±21.3bcd	58.4±1.5ab	37.9±1.2ab
		n2 (7:3:0)	7374.3±172a	426.7±5.8a	60.6±1.7a	37.9±0.9ab
		n3 (1:1:1)	5547.5±68cd	295.7±2de	54.3±1.5abc	35.2±1.1bc
		ck (0:0:0)	2164±129e	175.75±47f	40.0±2.1d	29.6±2e
	s3	n1 (1:0:0)	6467±275b	334±48bcd	56.5±2.7abc	41±0.9a
		n2 (7:3:0)	7335±698a	404.6±11ab	58±2.9abc	38.2±1.6ab
		n3 (1:1:1)	5229±132d	226.1±22ef	52.6±3bc	36.4±1abc
		ck (0:0:0)	1912.05±138e	157.95±22f	42.6±5d	36.2±5.05bc
straw		*	**	*	*	
nitrogen		***	***	***	***	
years			ns	*	*	
straw * nitrogen		***	***	***	**	
straw * years		**		ns	ns	ns
nitrogen * years			ns	ns	ns	ns
straw * nitrogen * years			ns	ns	ns	ns

Effect of rice straw return (s1: 100% straw incorporation; s2: 50% straw incorporation; s3: 0% straw incorporation) and nitrogen fertilizer strategies (n1: 180 kg N ha⁻¹ at basal; n2: 126 kg at basal + 54 kg at overwinter; n3: 60 kg at basal + 60 kg at overwinter + 60 kg at jointing, and control (ck: no nitrogen)) on GY: grain yield; SP: Spike number per hectare; TGW: Thousand grain weight; . Different lowercase letters indicate significant differences ($p < 0.05$) between treatments ($n = 4$). Symbols ***, **, * and ns indicate significance at $p < 0.001$, $p < 0.01$, $p < 0.05$, and non significant, respectively.



Field SPAD and LAI

The wheat flag leaf SPAD (Soil Plant Analysis Development) values were measured using a portable photosynthetic instrument SPAD-502 (Konica Minolta, Japan) at 0, 7, 14, 21, and 28 days after flowering. Fifteen flag leaves were measured for each treatment, and the average data were recorded. The LAI (Leaf Area Index) values were assessed using the Sunscan LP-80 plant canopy analyzer at the same time points. A light-sensing probe, 1 m in length with a photosensitive area of 0.01 m², was placed with the photosensitive side facing up at a distance of 0.5 m from the ground and the top of the wheat. Each measurement was repeated four times, and the average value was calculated.

Statistical analysis

The data were collated, organized, and validated using Microsoft Excel 2018. Initial tests for the basic assumptions of analysis of variance (ANOVA) and Tukey tests were conducted with IBM SPSS Statistics version 29.0.2.0, utilizing a 95% confidence interval to identify significant differences among treatments. Correlation analysis was performed using Origin Pro 2024b to explore relationships between various variables. The climate data (average

monthly precipitation and temperature) was provided by the Jingzhou prefecture meteorological office.

Results

Effects of straw return rates and nitrogen application timings on wheat yield and yield components

Rice straw return ($p < 0.05$) and nitrogen fertilization strategy ($p < 0.001$) significantly impacted wheat grain yield across both growing seasons (as shown in Table 2), with the s₂-n₂ treatment (50% straw return + 126 kg ha⁻¹ basal + 54 kg ha⁻¹ overwinter split-N) consistently yielding highest (7,384 ± 173 kg ha⁻¹ in 2021-2022; 7,374 ± 172 kg ha⁻¹ in 2022-2023). Across all straw treatments (s₁, s₂, s₃), yield followed n₂ > n₁ > n₃ > ck, where n₂ showed 7-19% and 26-32% advantages over n₁ and n₃, respectively, in 2021-2022, with similar trends in 2022-2023 (7-13% and 22-28%). These differences were driven primarily by spike numbers (393-432 × 10⁴ ha⁻¹ for n₂ vs 331-373 × 10⁴ ha⁻¹ for n₁ and 144-185 × 10⁴ ha⁻¹ for ck). Under n₂, yields ranked s₂ > s₁ > s₃, with s₂-n₂ outperforming s₁-n₂ by 5.1-6.5% and s₃-n₂ by 12.8-13.0%, demonstrating that 50% straw retention with split-N application maximized yield through enhanced spike formation while avoiding the yield penalty of full straw

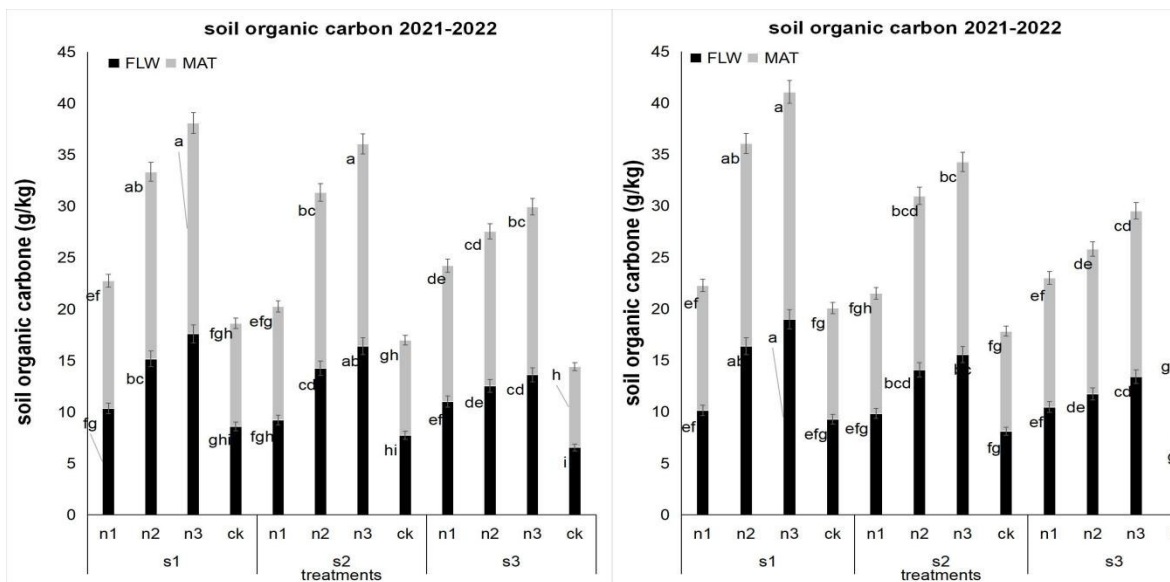


Figure 2: Effect of rice straw return (s₁: 100% straw incorporation; s₂: 50% straw incorporation; s₃: 0% straw incorporation) and nitrogen fertilizer strategies (n₁: 180 kg N/ha at basal; n₂: 126 kg at basal + 54 kg at overwinter; n₃: 60 kg at basal + 60 kg at overwinter + 60 kg at jointing and ck: no nitrogen) on wheat soil organic carbon during the flowering stage (FLW) and the maturity stage (MAT) across 2 cropping seasons (2021–2022, 2022–2023). Bars represent treatment combinations. Lowercase letters indicate significant differences ($p < 0.05$) within stages; values are means of 4 replicates ($n = 4$)



incorporation, maintaining $\geq 15\%$ advantages over conventional practice (s_3-n_1) regardless of annual variability.

Effects of straw return rates and nitrogen application timings on soil fertility parameters

Soil organic carbon

As shown in Figure 2, rice straw return and nitrogen fertilizer strategy significantly ($p < 0.05$) impacted the flowering and maturity soil organic carbon content (SOC), with consistent results between the two growing seasons. Comparing the different nitrogen strategies for all straw return conditions (s_1, s_2, s_3), SOC followed a consistent order of $n_3 > n_2 > n_1 > ck$. In 2021 - 2022, n_3 soc was 8.8–12.7% higher than n_2 (16.3–20.5 vs. 15.0–18.2 $g\ kg^{-1}$), 55.1–78.1% higher than n_1 (16.3–20.5 vs. 11.0–13.2 $g\ kg^{-1}$), and 104.8–107.9% higher than ck (16.3–20.5 vs. 6.6–10.0 $g\ kg^{-1}$) at the maturity stage and showed similar advantages. In 2022 – 2023, comparing the effect of different straw returns under all the nitrogen fertilizer strategy, the SOC result presented a consistence order of $s_1 > s_2 > s_3$ for the 2 growth season and the flowering and maturity stages, for example for n_3 at the maturity stage, In 2021 - 2022, $s_1 - n_3$ (20.5 $g\ kg^{-1}$) outperformed $s_2 - n_3$ by 4.2% and $s_3 - n_3$ by 25.4%. In 2022

- 2023, the advantage was 18.2% and 37.1% higher than $s_2 - n_3$ and $s_3 - n_3$, respectively. Over two growing seasons, $s_1 - n_3$ treatments consistently obtain the most advantageous SOC content (22.1 $g\ kg^{-1}$) that was 55.1–81.5% higher than the regional conventional practice ($s_3 - n_1$: 12.6–13.2 $g\ kg^{-1}$).

Soil N, P, and K content

As shown in Table 3, straw return and nitrogen fertilization significantly ($p < 0.05$) influenced soil N, P, and K levels during both 2021-2022 and 2022-2023 growing seasons, demonstrating consistent treatment effects where n_3 (split application) $> n_2 > n_1 > ck$ for nitrogen strategies and s_1 (full return) $> s_2 > s_3$ for straw management. The n_3 treatment yielded peak nutrient concentrations across both seasons: N reached 0.64 $g\ kg^{-1}$ (FLW 2021-2022, $s_1 - n_3$) and 0.38 $g\ kg^{-1}$ (MAT 2021-2022, $s_2 - n_3$), P peaked at 75.0 $mg\ kg^{-1}$ (FLW 2021-2022, $s_1 - n_3$), and K achieved 232.75 $mg\ kg^{-1}$ (FLW 2021-2022, $s_2 - n_3$), representing increases of 95–191% (N), 25–45% (P), and 35–80% (K) over the control (ck). Full straw return (s_1) further enhanced these effects, with $s_1 - n_3$ combinations showing consistent advantages of 4.2–25.4% (N), 10–20% (P), and 15–30% (K) over partial (s_2) or no straw (s_3) treatments. These results demonstrate

Table 3: Impact of straw return rates and nitrogen application timings on soil total N/P/K at flowering (flw) and maturity (mat) stages Abbreviations must be given in the foot note like nitro, SN,FLW, SN Mat, SK

Years	Straw	Nitro	SN. FLW ($g\ kg^{-1}$)	SN. Mat ($g\ kg^{-1}$)	SP. FLW($mg\ kg^{-1}$)	SP. MAT ($g\ kg^{-1}$)	SK. FLW ($mg\ kg^{-1}$)	SK. Mat($mg\ kg^{-1}$)
2021 -2022	s1	n1 (1:0:0)	0.37±0.02c	0.24±0.017d	58.8±2e	41.1±1.39de	168.05±3.13f	131.1±2.44e
		n2 (7:3:0)	0.43±0.01bc	0.27±0.006cd	61.8±1.6cde	41.67005±1.05de	184.7±5.8cde	134.8±10.8de
		n3 (1:1:1)	0.59±0.01a	0.34±0.03ab	69.8±1.4a	48±1.6ab	194.2±5.3bcd	151.5±4.1bc
		ck (0:0:0)	0.2±0.02cd	0.12±0.018e	51.7±1f	38.4±2.41ef	143.85±8.9g	100.8±8.9f
	s2	n1 (1:0:0)	0.45±0.05b	0.28±0.023cd	59.7±1.4de	46.9±1.1bc	201.66±3.75b	145.6±2.80bc
		n2 (7:3:0)	0.49±0.04b	0.30±0.026bc	64.9±2.5bc	49.6±2.42ab	221.4±6.94a	161.15±5.05b
		n3 (1:1:1)	0.6±0.025a	0.38±0.023a	71.5±1.9a	51.3±1.3a	232.75±6.56a	181.5±5a
		ck (0:0:0)	0.21±0.02d	0.13±0.01e	53.2±0.9f	38.5±0.63ef	172.62±10.7ef	134.6±8.4de
	s3	n1 (1:0:0)	0.4425±0.02b	0.27±0.016cd	59.85±0.48de	41.9±0.3de	174.3±4.7ef	135.9±3.7de
		n2 (7:3:0)	0.49±0.02b	0.29±0.01bc	63±1.3cd	44.1±0.9cd	178.75±1.85def	139.4±1.4bcd
		n3 (1:1:1)	0.575±0.03a	0.33±0.015b	68.45±1.1ab	47.1±1.97bc	196.1±7.89bc	153±6.15bc
		ck (0:0:0)	0.195±0.04d	0.11±0.02e	52.9±1f	37.0±0.7f	137.4±4.08g	107.2±3.18f
2022 -2023	s1	n1 (1:0:0)	0.36±0.02e	0.24±0.017c	57.5±1.9cdef	40.3±1.4cd	164.5±3.06cde	128.3±2.4cd
		n2 (7:3:0)	0.46±0.03cd	0.29±0.026b	66.7±4.2abc	44.9±2.9bcd	199.68±20.69ab	145.3±14.6bc
		n3 (1:1:1)	0.64±0.06a	0.37±0.05a	75±7.1a	51.86±5.52a	209.8±19.6ab	163.7±15.3ab
		ck (0:0:0)	0.22±0.01f	0.13±0.01d	55.87±5.3ef	41.4±3.5cd	155.3±16.2ab	108.7±12.2d
	s2	n1 (1:0:0)	0.44±0.05d	0.27±0.02bc	58.99±1.4bcdef	46.4±1.1abc	199.2±3.7ab	143.8±2.8bc
		n2 (7:3:0)	0.49±0.04cd	0.29±0.025b	64.1±2.48bcde	48.96±2.4ab	218.7±6.9a	159.16±4.99ab
		n3 (1:1:1)	0.57±0.02ab	0.36±0.021a	67.9±1.81ab	48.7±1.27ab	221.1±6.2a	172.5±4.8a
		ck (0:0:0)	0.23±0.02f	0.13±0.01d	55.9±0.91def	40.4±0.7cd	181.3±11.299bcd	141.4±8.8bc
	s3	n1 (1:0:0)	0.42±0.02de	0.25±0.016bc	56.8±0.45def	39.8±0.32d	165.6±4.48cde	129.1±3.49cd
		n2 (7:3:0)	0.46±0.03cd	0.28±0.007bc	59.0±1.2bcdef	41.3±0.8cd	167.4±3.7ede	130.6±2.9cd
		n3 (1:1:1)	0.52±0.03bc	0.3±0.015b	65.0±1.04bcd	46.36±3.7abc	193.6±21.5abc	151±16.8abc
		ck (0:0:0)	0.18±0.03f	0.10±0.02d	54.1±7.04f	40.4±0.8cd	149.8±4.4e	116.8±3.5d
straw	***	***	***	**	***	***	***	
nitro	***	***	***	***	***	***	***	
years		ns	ns	ns	ns	ns	ns	
straw * nitro	***	**	ns	ns	**	ns	ns	
straw * years		**	*	***	**	**	*	
nitr * years		ns	ns	ns	ns	*	ns	
straw * nitr * years		ns	ns	ns	ns	*	ns	



that split nitrogen application (n3) combined with full straw return (s1) reliably optimizes soil nutrient availability across growth stages and seasons.

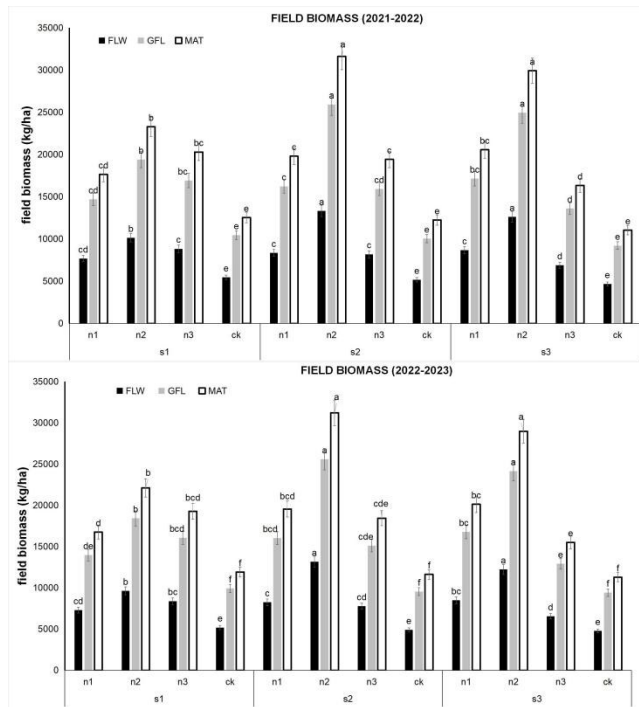


Figure 3: Effect of rice straw return (s1: 100% straw incorporation; s2: 50% straw incorporation; s3: 0% straw incorporation) and nitrogen fertilizer strategies (n1: 180 kg N ha⁻¹ at basal; n2: 126 kg at basal + 54 kg at overwinter; n3: 60 kg at basal + 60 kg at overwinter + 60 kg at jointing, and control (ck: no nitrogen)) on field biomass (kg ha⁻¹) at three growth stages: FLW: flowering; GFI: grain filling; MAT: maturity. Different lowercase letters indicate significant differences ($p < 0.05$) between nitrogen treatments within the same straw level and growth stage ($n = 4$)

Impact of straw return rates and nitrogen application timings on field dry matter

As shown from Figure 3, straw and nitrogen treatments significantly ($p < 0.05$) influenced biomass accumulation from flowering through maturity, showing consistent patterns across both seasons. The nitrogen response hierarchy ($n2 > n3 > n1 > ck$) remained stable, with the n2 strategy achieving peak biomass of 31,604 kg ha⁻¹ at maturity (s2-n2, 2021-2022) - a 158% increase over control (12,240 kg ha⁻¹) and 60% higher than conventional practice (19,786 kg ha⁻¹).

During grain filling, s2-n2 produced 25,905 kg ha⁻¹, outperforming s2-n1 by 60% (vs 16,218 kg ha⁻¹). The s2-n2 combination yielded 36% greater maturity biomass than s1-n2 (23,266 kg ha⁻¹) and exceeded no-straw controls by 186% (vs 11,040 kg ha⁻¹). Stage-specific analysis revealed n2 advantages of 57% at flowering (13,113 vs 8,341 kg ha⁻¹ in s2), 60% at grain filling, and 158% at maturity versus controls.

Impact of straw return rates and nitrogen application timings on plant LAI -SPAD

As demonstrated in Figures 4-5 and supporting data, the s2-n3 treatment (50% straw incorporation with three-split nitrogen application) consistently produced superior photosynthetic performance and canopy development across both growing seasons. For instance, at 14 days after flowering (DAF), s2-n3 achieved peak SPAD values of 83.1 (52% higher than conventional s3-n1 (54.5) and 111% higher than control s3-ck (39.3)), s2-n3 reaching the 14th DAF with LAI of 4.65 (33% and 88% greater than s3-n1 3.50 and s3-ck 2.48, respectively). The treatment hierarchy was unequivocal, with nitrogen responses following $n3 > n2 > n1 > ck$ and straw effects showing $s2 > s1 > s3$. Most critically, s2-n3 sustained physiologically important thresholds longer than other treatments, maintaining SPAD ≈ 60 for 21 days (versus 14 days in conventional) and LAI ≥ 3 for 28 days (versus 14 days), demonstrating its exceptional capacity to prolong photosynthetic activity during grain-filling. These results establish that moderate straw retention with staged nitrogen application optimally supports late-season photosynthetic performance in rice, providing a scientifically validated strategy to enhance productivity while maintaining treatment integrity throughout the reproductive phase.

Discussion

Straw return is a proven practice for enhancing soil organic carbon (SOC) (Xin *et al.*, 2024), yet its effects on crop yields vary significantly with management practices (Islam *et al.*, 2022). This study demonstrates that 50% straw return (s2) combined with split-N application (n2) optimized wheat yields (7,384 kg ha⁻¹), outperforming conventional practices by 15-19%. This aligns with global findings that moderate straw retention (30-60%) with staged N fertilization balances yield and soil health (Usman *et al.*, 2014; Ruo-Chen Li *et al.*, 2024), while excessive straw incorporation can reduce yields due to N immobilization (Liu *et al.*, 2019) or phytotoxic effects (Jin *et al.*, 2020). These results highlight the critical importance of tailoring straw and N management to local conditions.



Impact of straw return and nitrogen splitting strategy on wheat grain yield and yield components

The optimization of straw management and nitrogen application timing remains a critical challenge in wheat production systems. Limon-Ortega *et al.* (2008) established that while straw burning could improve yield and nitrogen use efficiency compared to incorporation, the environmental consequences of burning necessitated alternative approaches.

Recent advances have demonstrated the potential of partial straw return systems, with (Li *et al.*, 2025) showing that 1/2 straw return (1/2SN) with optimized nitrogen rates increased yields by 7.6-12.7%, though the ideal straw incorporation rate required further refinement. Complementary research on nitrogen application timing by and (Belete *et al.*, 2018) revealed that strategic nitrogen splitting - whether through equal basal-topdressing (5:5) or three-stage applications (1/4 sowing, 1/2 tillering, 1/4 booting) - could significantly enhance yields by improving photosynthesis allocation and spike

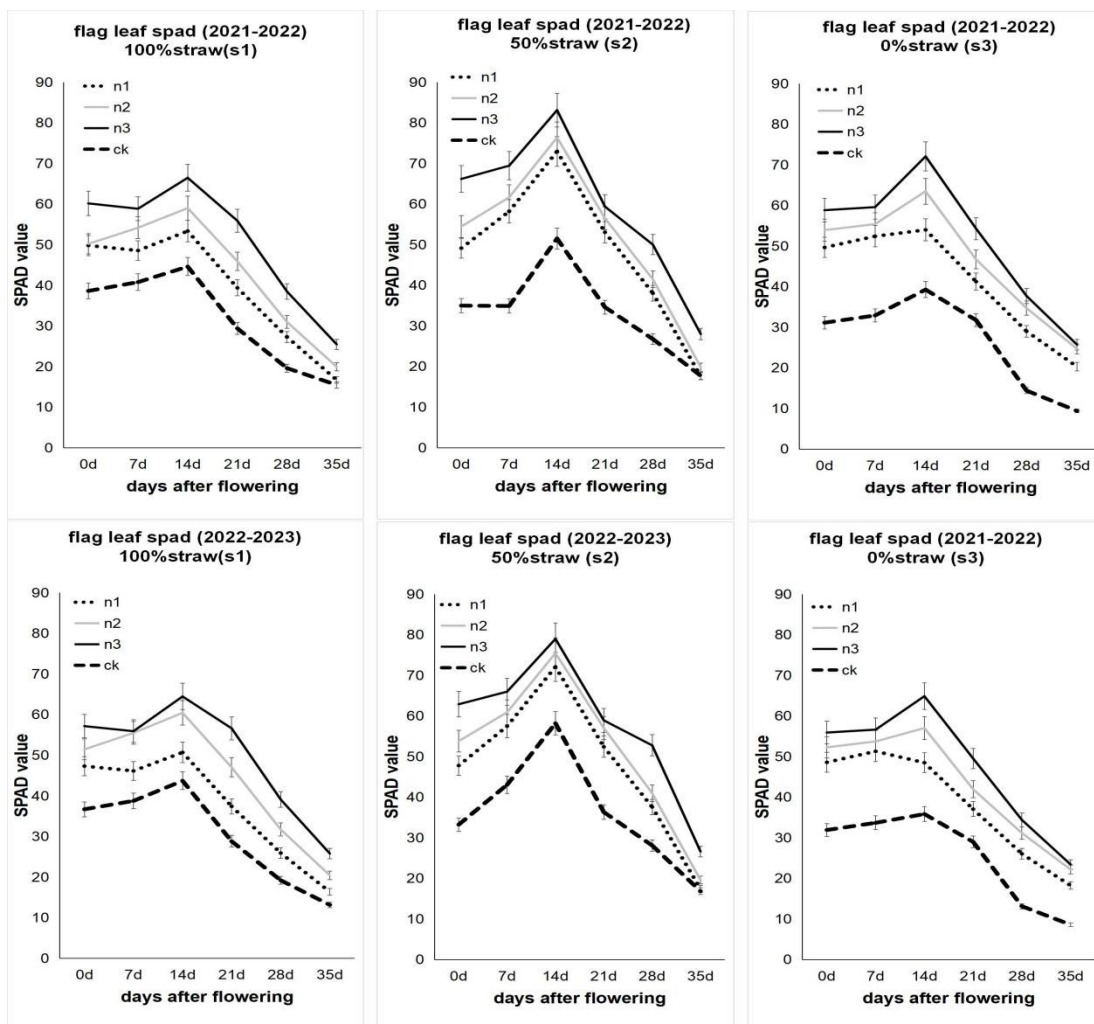


Figure 4: Effect of rice straw return (s1: 100% straw incorporation; s2: 50% straw incorporation; s3: 0% straw incorporation) and nitrogen fertilizer strategies (n1: 180 kg N ha⁻¹ at basal; n2: 126 kg at basal + 54 kg at overwinter; n3: 60 kg at basal + 60 kg at overwinter + 60 kg at jointing, and control (ck: no nitrogen)) on flag leaf SPAD values (chlorophyll content index) at after the flowering . Different lowercase letters indicate significant differences ($p < 0.05$) between nitrogen treatments within the same straw level and growth stage ($n = 4$)

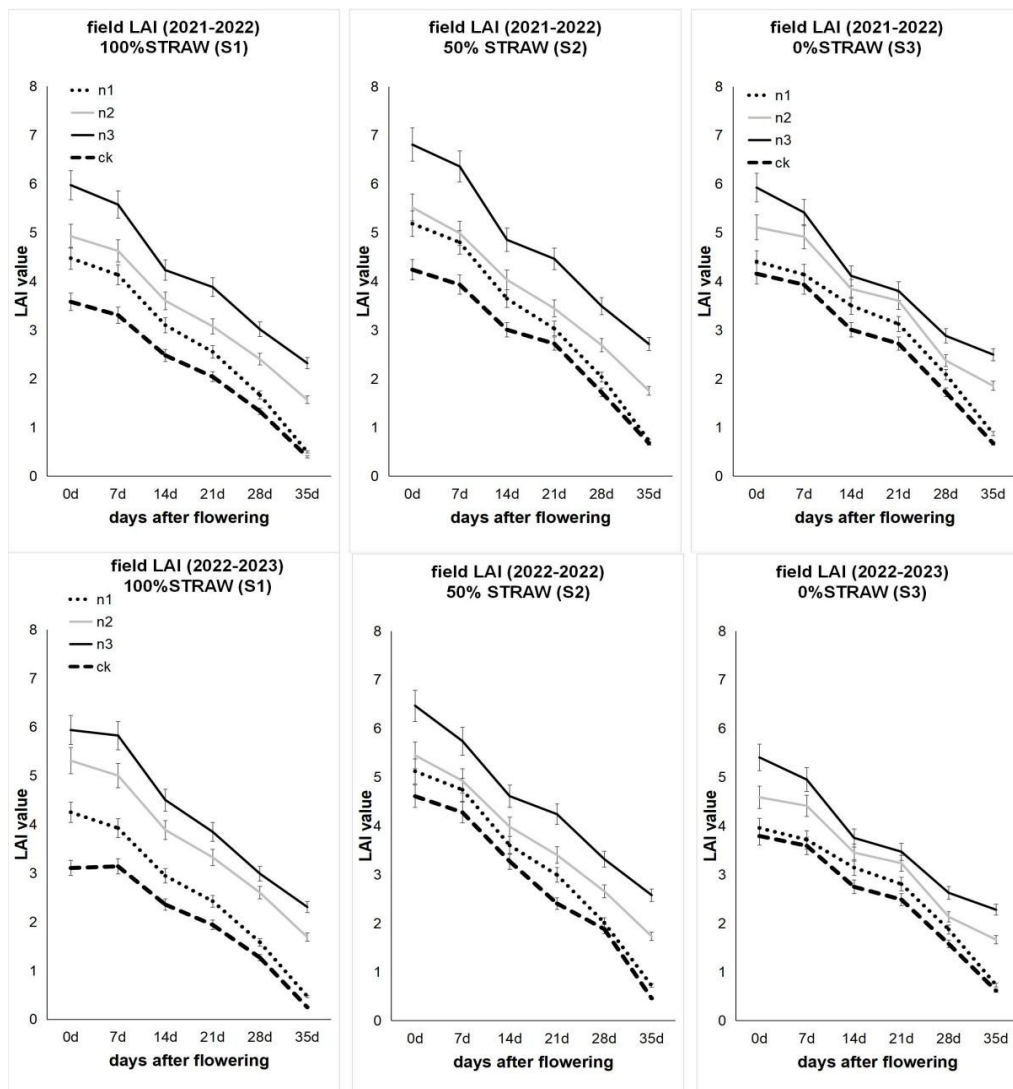


Figure 5: Effect of rice straw return (s1: 100% straw incorporation; s2: 50% straw incorporation; s3: 0% straw incorporation) and nitrogen fertilizer strategies (n1: 180 kg Nha^{-1} at basal; n2: 126 kg at basal + 54 kg at overwinter; n3: 60 kg at basal + 60 kg at overwinter + 60 kg at jointing, and control (ck: no nitrogen)) on LAI (Leaf Area Index) after the flowering. Different lowercase letters indicate significant differences ($p < 0.05$) between nitrogen treatments within the same straw level and growth stage ($n = 4$)

development. The study advances these findings by precisely quantifying the optimal straw incorporation rate, demonstrating that 50% straw return (s₂) combined with a two-split nitrogen application (126 kg ha^{-1} basal + 54 kg ha^{-1} overwinter) achieved superior yields of 7,384 kg ha^{-1} . This system provided a 13-32% yield advantage over conventional practices while maintaining environmental sustainability, with spike numbers (393-432 $\times 10^4/\text{ha}$) confirming efficient nitrogen utilization during critical growth stages, consistent

with the physiological mechanisms described by Zhang *et al.* (2021).

Impact of straw return and nitrogen splitting strategy on wheat soil fertility parameters

The results demonstrate that straw return combined with split nitrogen application significantly enhanced soil fertility. The s₁-n₃ treatment (full straw return with three-



split nitrogen) achieved the highest SOC (22.1 g kg^{-1}) and N,P,K nutrient levels, consistent with Huang *et al.* (2021) who reported straw incorporation increased SOC and available nutrients in the 0–20 cm layer. The higher nitrogen increase under n_3 aligns with Xing Wang *et al.* (2019) showing split applications improve N recovery by 24.6%, while SOC improvements exceed 22% increase in rice-wheat systems. These effects are supported by Cui *et al.* (2022) 8-year nitrogen fraction data and Borny *et al.* (2024) findings on microbial enhancement under combined treatments. This study on nitrogen timing strategy confirms López - Bellido *et al.* (2006) recommendation for split applications between tillering and stem elongation. The research of (Wang *et al.* (2022) Li *et al.* (2023), Zhang *et al.* (2024) and Guo *et al.* (2025), also showed that returning straw increased soil organic carbon content, and the finding where aligned with the current study result.

Impact of straw return and nitrogen splitting strategy on field dry matter

The treatment of 50% straw return with split nitrogen significantly enhanced dry matter accumulation, ($31,604 \text{ kg ha}^{-1}$) at maturity - a 158% increase over control and 60% advantage over conventional practice. These findings align with Duan *et al.* (2025) wheat study showing how straw return boosts dry matter at key growth stages, while the present study quantified nitrogen response hierarchy ($n_2 > n_3 > n_1 > \text{ck}$) confirms Han and Wenqian (2024) observation that 7:3 nitrogen splits outperform 3:7 ratios under straw return. Notably, s_2 - n_2 treatment's 36% superiority over full straw return (s_1 - n_2) supports Wang *et al.* (2022) finding that medium straw quantities optimize biomass accumulation while avoiding allelochemical effects observed in Hicks *et al.* (1989) decomposition studies.

Impact of straw return and nitrogen splitting strategy on plant leaves SPAD and LAI

Enhanced photosynthetic performance under 50% straw return + three-split nitrogen was evidenced by peak SPAD (83.1) and LAI (4.65) at 14 DAF, along with extended photosynthetic duration (SPAD \approx 60 for 21 days; LAI \geq 3 for 28 days)—stems from synergistic resource optimization. This aligns with Zhang *et al.* (2021), where staged nitrogen applications enhanced photosynthate mobilization and chlorophyll retention (SPAD +18–22%) by matching nitrogen release to reproductive demand. The 50% straw threshold proved critical: it avoided light limitation and allelochemical suppression observed in full-return systems (Hicks *et al.*, 1989; Wang *et al.*, 2022), while improving microclimate regulation and nutrient mineralization. Consequently, s_2 - n_3 's 52–111%

SPAD advantage and 33–88% LAI gain over controls reflect efficient nitrogen partitioning (reducing leaching by 41.7% per (Zhao *et al.*, 2019) and sustained canopy functionality. These mechanisms reconcile seemingly contradictory literature: while single-dose nitrogen depletes too early (n_1), and full straw (s_3) inhibits growth, moderate straw + staged nitrogen approach extends active photosynthesis 50–100% longer than conventional practices—directly explaining its 9.5–12.2% yield advantage in grain-filling stages (Zhang *et al.*, 2022).

The current study underscores that optimizing both the quantity of straw return and the nitrogen (N) fertilizer rate and timing at key growth stages is paramount for significantly impacting wheat growth, yield, and soil characteristics. This study results, showing superior soil fertility at flowering and maturity under straw return, align with research indicating that straw decomposition gradually releases valuable nutrients at later stages (Huandi Li *et al.*, 2024). However, this benefit is nuanced; the high carbon-to-nitrogen (C:N) ratio of straw can lead to significant N immobilization by soil microbes at early decomposition stages, potentially imbalance the soil C:N ratio and hindering early crop growth and soil fertility (Bhogal *et al.*, 1997; Xing Wang *et al.*, 2019). Indeed, excessive straw application can prolong decomposition, intensify microbial N consumption, increase nutrient loss through enhanced soil porosity, and even promote pathogen growth, thereby negatively impacting crop productivity (Shan YuHua *et al.*, 2006; Tian *et al.*, 2022). This explains why 50% straw retention outperformed full straw incorporation, a finding supported by recommendations for moderate straw application (30–50%) to balance organic matter benefits with nutrient availability (Li *et al.*, 2025). Future research should therefore focus on the dynamics of soil fertility and crop health during earlier growth stages to further validate these hypotheses. Furthermore, acknowledging the limitations of the present study, which was conducted in a single region, soil type, and with one wheat variety, future investigations should consider multiple geographic locations and diverse wheat cultivars. This broader approach will be crucial for filling existing knowledge gaps and developing more universally applicable sustainable agricultural practices.

Conclusion

This study conclusively demonstrates that optimizing both rice straw return and nitrogen (N) fertilizer splitting strategies is paramount for sustainable winter wheat production. The specific treatments explored were: s_1 = full straw return, s_2 = 50% straw return, s_3 = no straw return; n_1 = conventional N, n_2 = 126 kg ha^{-1} basal + 54 kg ha^{-1} overwinter, n_3 = three-split N application; and ck = control



(no N fertilizer). The combination of 50% straw return (s_2) with a two-split nitrogen application (n_2) maximized grain yield through enhanced spike development, while full straw return (s_1) integrated with a three-split nitrogen application (n_3) significantly enriched soil organic carbon and nutrient availability, fostering long-term soil fertility. These optimized practices synergistically improved biomass accumulation and prolonged photosynthetic activity. The findings highlight the critical importance of balancing straw quantity to mitigate potential nitrogen immobilization, emphasizing that moderate incorporation is key. While robust, this study was confined to a single region, soil type, and wheat variety. Future research should expand to diverse geographical locations and cultivars to validate these findings and investigate earlier growth stage dynamics for more universally applicable sustainable agricultural practices.

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Conflicts of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Authors' contribution statement

KSPD conceived the study, organized and carried out the experiment, and wrote the initial manuscript draft, ML, YY, GHA, and ZJQ contributed to the experiment's conception and execution, and manuscript editing. XW supervised and financed the study, supervised and corrected the manuscript editing process.

Availability of data and material

Additional tables, raw data, supporting information, and image of the field at different growth stage are available and will be provide on demand from the first author KSPD (pavelsenou@qq.com).

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