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Impact of Rice–Wheat Straw Incorporation and Varying Nitrogen Fertilizer Rates on Soil Physicochemical Properties and Wheat Grain Yield

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Abstract: Straw return (SR) is crucial for the comprehensive and efficient utilization of resources within agroecosystems; however, its impact on soils and wheat grain yield in the Jianghan Plain of the Yangtze River Basin, Hubei Province of China, is not fully known. Therefore, the present study was undertaken to assess the impact of returning rice–wheat straw, along with different nitrogen (N) fertilizer applications, on soil physicochemical properties and wheat grain yield. The Yangmai 23 wheat variety was cultivated in the Experimental Farms of Yangtze University in the Yangtze River Basin, with three rates of rice SR (0, 50 and 100%) and four N fertilizer rates (0, 33.3, 70 and 100%) with 180 kg/ha urea. The integrated use of SR- and N-fertilizer rates significantly altered soil nitrogen, nitrate, ammonium, phosphorus, potassium, pH and moisture within the 20 cm depth before the seeding, jointing and maturation stages of the wheat. The grain yields of $6408 \pm 110 - 8290.00 \pm 298$ and $4726 \pm 62 - 6758.00 \pm 196$ kg/ha were obtained in the 2021–2022 and 2022–2023 seasons, respectively. The studied soil physicochemical properties either before seeding, or at the jointing and maturation stages had a significant effect on final grain yield. These results underscore the combined effect of SR- and N-fertilizer application to improve wheat productivity in the Yangtze River Basin. However, further studies are ongoing to assess the impact of these treatments on the soil microbial community, as well as on wheat grain quality.

Keywords: inorganic fertilizers; soil fertility management; soil conservation; straw management; sustainable wheat production

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1. Introduction

Wheat (*Triticum aestivum* L.) is a highly cultivated crop on a global scale, with China serving as the leading producer, accounting for 17% of the world's total wheat production [1]. According to several studies [2–4], winter wheat constitutes approximately 95% of the overall wheat production in China, encompassing both winter and spring varieties. The combined global production of wheat and the aggregate volume of wheat traded amount to 770 and 481 million tons, respectively. This substantial quantity of wheat serves as a primary food source for approximately 35% of the global population, contributing to over 20% of the total caloric intake for humans and supplying approximately 20% of the protein consumed worldwide [2,5,6]. According to the most recent data by FAO [1], enhanced wheat production prospects have contributed to a rise in overall global grain production. However, despite this improvement, the projected grain production for the 2021/22 period failed to meet the anticipated consumer demand, leading to a decrease in global stocks. China, being a nation with a long-standing history in agriculture, annually generates approximately 1.04 billion metric tons of crop straw [7].

In recent years, there has been a notable rise in the production of rice (*Oryza sativa* L.) and wheat (*T. aestivum* L.) straws, which can be attributed to consistent growth in rice and wheat cultivation. As a consequence of economic progress and enhanced quality of life, crop straw has undergone a transition from its previous role as a source of energy and animal feed to being classified as agricultural waste [8,9]. In the course of agricultural production, farmers engage in the practice of burning crop straw to maintain the pace of their farming operations, minimize labor and material resource usage, and alleviate unnecessary exertion. However, this practice has adverse consequences on the environment and has a detrimental impact on both human productivity and quality of life. Furthermore, it leads to the squandering of valuable natural resources and exerts considerable strain on the soil ecosystem [10–12]. Hence, the utilization of burnt rice and wheat straw resources has emerged as a significant environmental concern.

Crop straw is abundant in organic matter and essential nutrient elements that are crucial for promoting plant growth. The act of reintroducing straw back into the field has the potential to introduce a substantial quantity of organic matter into the soil [13–15]. This process triggers a sequence of intricate biochemical reactions within the soil ecosystem, including nitrogen mineralization and the priming effect resulting from organic matter decomposition. These reactions have the capacity to markedly enhance soil quality [16–18]. Crop straw is a carbonaceous energy resource that possesses significant quantities of nitrogen, phosphorus, potassium, and other essential nutrients required for crop development [6,19]. Its utilization plays a crucial role in mitigating imbalances in the nitrogen, phosphorus, and potassium ratios within agricultural soil, as well as compensating for deficiencies in phosphorus and potash mineralization [6]. Straw returning is a highly efficient method for addressing the issue of excessive straw treatment, while also mitigating the environmental pollution associated with straw burning. Simultaneously, the process of straw decomposition yields nutrients that can be utilized to enhance soil fertility, create favorable conditions for microbial proliferation in the soil, stimulate crop growth, and ultimately augment crop yield [12,20,21]. This practice is considered crucial for the comprehensive and efficient utilization of resources within agroecosystems, as it significantly contributes to the maintenance of a robust soil fertility cycle and the promotion of sustainable agricultural development.

Soil organic carbon encompasses carbon present in humus, as well as animal and plant residues, and microorganisms that are generated through microbial processes within the soil [18,22]. It serves as the primary source of carbon nutrients essential for the sustenance of plant and biological life within the soil. Furthermore, soil organic carbon significantly influences the physicochemical properties of the soil. Its concentration within the soil is heavily influenced by the composition and abundance of soil microorganisms. The presence of soil organic carbon plays a crucial role in governing its physicochemical and biological properties/reactions, thereby enhancing soil fertility. The accumulation and conversion of soil organic carbon can have direct or indirect impacts on soil water dynamics, nutrient availability, gas exchange, thermal regulation, and biochemical transformation [23–26]. Additionally, the levels of soil organic carbon are intricately linked to both soil quality and agricultural productivity [23–26].

Hence, it is imperative to study the fluctuations in the reservoir of soil organic carbon to uphold the sustainability of the global agroecosystem. The impact of straw return on soil has been extensively studied in terms of various environmental factors, such as soil water potential [15], temperature [3,15,27], enzyme activities [16,20], fractions of soil organic matter [7,9,22], soil quality and crop productivity [16–18], emissions of greenhouse gases from soil [20,28,29], soil physicochemical properties [19,30], and soil microbial communities [7,18,31,32]. Several studies have suggested that the practice of straw return has the potential to enhance the ecological environment of soils [4,11,17,29,33,34]. This is achieved through the promotion of antagonistic microbes, disruption of pathogen growth, and enhancement of plant resistance to pathogens; consequently contributing to the effective control of soil-borne plant diseases [26,29,35].

A study by Jaćimović et al. [4] demonstrated that the practice of straw return has the potential to alter the composition of soil microbial communities. The application of maize (*Zea mays* L.) straw at a rate of 9000 kg ha^{-1} resulted in an increase in total phospholipid fatty acid content when compared to the treatment without straw return. Additionally, this application of maize straw caused alterations in the structure of the microbial community [4,31]. The rapid decomposition of straw has a significant influence on soil microbes as it alters the microenvironment of the soil [14,15]. The combination of inorganic fertilizers and the incorporation of rice straw into the soil has been found to have a substantial impact on bacterial abundance, leading to changes in the composition of the bacterial community [7,33,36]. The application of chemical fertilizer leads to alterations in the microbial community structure, particularly in the presence of high rates of straw [37]. The addition of nitrogen (N) fertilizer to wheat and maize straw that was returned to the soil was found to enhance soil fertility and enzyme activity compared to the sole return of straw. This, in turn, leads to an improved composition of the bacterial community [7,37]. Prior study has demonstrated that the utilization of fertilizers and straw has the potential to enhance both the abundance and functionality of microorganisms, including fungi and bacteria, within soil. Furthermore, it has been observed that the composition and arrangement of the microbial community vary depending on the specific treatment applied [7,33,36,38].

The presence of straw residue has an impact on the tiller count per plant during the wheat seedling stage. Previous studies have provided evidence regarding the impact of maize straw return on soil physicochemical properties and microorganisms in various regions [4,26,28,39]. For instance, Arul et al. [39] recently reported varied impacts of maize straw on bacterial community and carbon stability at different soil depths. However, limited information exists regarding the influence of combining different topdressing nitrogen fertilizers and rice straw return on soil physicochemical properties and wheat productivity in the middle–lower Yangtze River Basin, specifically the Jianghan Plain. Consequently, an experimental study was undertaken to evaluate the interconnected impacts of wheat–rice straw incorporation and varying nitrogen fertilizer levels on wheat productivity in the Jianghan Plain. The practice of rice–wheat crop rotation dominates in Jianghan Plain [40]. However, the current study reports only the effect of rice–wheat straw and nitrogen fertilization on soil physicochemical properties and the grain yield of winter wheat. The primary aims of this study were (i) to assess the impact of combined SR and varied N fertilizer application with N fertilizer topdressing on soil quality and fertility through changes in physicochemical soil properties; and (ii) to assess the impact of returning rice–wheat straw on wheat yield.

2. Materials and Methods

2.1. Experimental Site Description and Planting Material

This study was conducted in the Jianghan Plain of Jinzhou City, Hubei Province, People's Republic of China (PRC), at the Experimental Farm Station (30036′ N, 112008′ E) of Yangtze University from 2021 to 2023, thus 2021–2022 and 2022–2023 winter wheat-cropping seasons, according to the local cropping calendar. The field is used for wheat and rice rotation. The Jianghan Plain is one of major grain production bases in Hubei Province, and forms a key part of the wheat-growing areas in the Yangtze River Basin [41]. The Experimental Farm Station is characterized by a typical subtropical monsoon climate in the middle–lower Yangtze River Basin of China. The area experiences relatively the same amount of rainfall and mean daily temperature during the two winter wheat growing seasons (Figure 1A,B). The soil type is calcareous alluvial with sandy loam texture [42]. For this study, the variety Yangmai 23 (YM23) was cultivated. Thus, YM23 is one of the main wheat varieties cultivated in both the middle and lower reaches of the Yangtze River in China [43]. Pure and healthy seeds of the YM23 variety (pedigree Yangmai 16 × Yangfu 93–11) were obtained from Jiangsu Golden Land Seed Industry Co., Ltd. (Jiangsu, China).

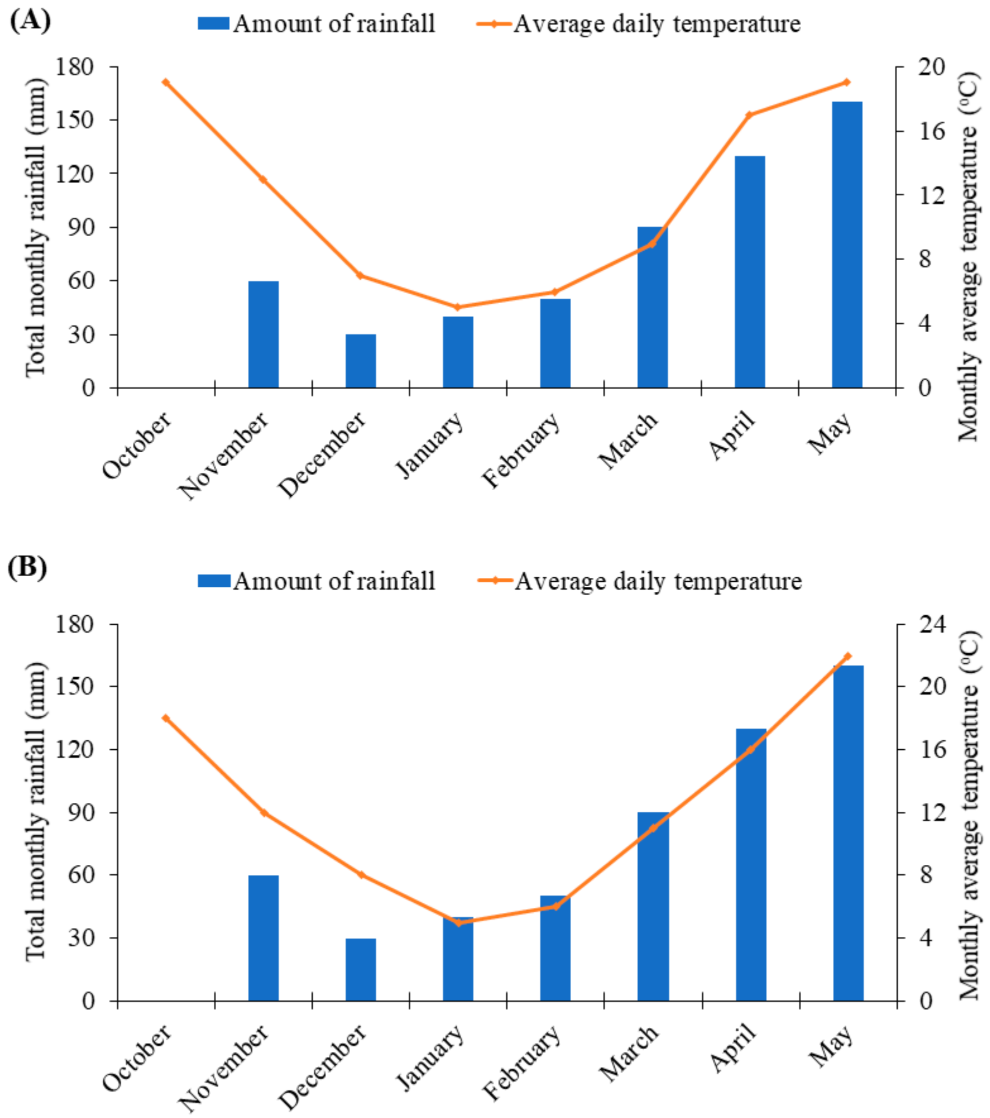

Figure 1. (**A**) Monthly total rainfall and (**B**) monthly mean temperatures recorded on-site in 2021–2022 and 2022–2023 winter wheat-growing seasons in the study area.

2.2. Experimental Design and Treatments

The experimental treatments were arranged in a randomized complete block design with three replications. In this study, 12 treatment combinations were used, including nitrogen fertilization (N) and straw return (SR) rates. Briefly, the N rates consisted of 0, 33.3, 70, and 100% N from urea (46% N), applied at different rates, each totaling 180 kg N/ha (Table 1), while the SR rates comprised 0, 50 and 100%. The experimental field was previously used for rice cultivation and the rice grains were harvested. Briefly, at 0 SR, all rice straw (both below and above ground) was removed and the field was cleaned manually (Figure 2A). In the case of 50% SR, all the straw was collected from the field, weighed, and 50% of it was returned to the field (Figure 2A). In the 100% SR treatment, no straw was collected from the field (Figure 2B). A tractor was employed to plow and harrow the demarcated plots of 0, 50 and 100% to a depth of 15 cm (Figure 2C). In all, the 12 treatments were coded T1–T12 (for details see Table 1). The total experimental area was 78 m in length and 29 m in width. Planting and other cultural practices were carried out according to the conventional practices in the study area. In brief, plots were supplied with phosphorus (P) fertilizer at the rate of 105 kg P_2O_4/ha (with calcium superphosphate) and potassium (K), at the rate of 105 kg K_2O/ha with K sulfate fertilizer, during the sowing time. Other operations such as herbicide, pesticide and fungicide application were carried out according to conventional practices, to prevent yield losses.

Table 1. Treatment combination structure of N (180 kg N/ha) and SR rates in this study.

N Rates (%)	Stage and N Amount Applied (kg N/ha)			Rice Straw Return Rate (%)		
	Sowing	Wintering	Jointing	0	50	100
0.00	0	0	0	T1	T2	T3
33.30	60	60	60	T4	T5	T6
70.00	126	54	0	T7	T8	T9
100.00	180	0	0	T10	T11	T12

Figure 2. Experimental field preparation. (**A**). Zero rice-paddy straw return (SR) plot (left) and 50% SR plot (right). (**B**). 100% SR plot. (**C**). Ploughed and harrowed plot of 100% SR.

2.3. Data Collection

2.3.1. Soil Sampling and Physiochemical Analyses

Soil samples were collected at three stages, i.e., before seeding (BF), and at the jointing stage (JT) and maturation stage (MT), at the depth of 20 cm, following recommended procedures [31]. In brief, five soil samples from each plot were obtained and mixed as composite sample. Firstly, the soil water content was quantified by drying the soil samples in an oven at 105 °C until reaching a constant weight [20,44], and the soil moisture content was obtained by the formula below:

$$Soil\ moisture\ (\%) = \frac{Fw - Dw}{Dw} \times 100\%$$

where Fw and Dw represent the fresh and dried weight of soil sample.

The soil pH was determined in water (1:2.5 w/v) using a pH meter (PHS-3C, INESA Scientific Instrument Co. Ltd., Shanghai, China). The total nitrogen, nitrate (NO_3^-) and ammonium (NH_4^+) contents were determined using semi-microkelvin, the ultraviolet spectrophotometry–colorimetric method, and the indophenol blue colorimetric method, respectively, with minor modifications [44]. The total available phosphorus content was determined using the sodium hydroxide melting–molybdenum antimony colorimetric method, with slight modifications [21,44]. Available potassium (K) in soil was quantified by 1 M NH_4OAc (pH 7.0) with a liquid-to-solid ratio of 10:1, and the K level was finally determined by flame photometer [45]. All soil analyses were carried out in the soil chemistry laboratory of College of Agriculture, Yangtze University. All analyses were carried out for the three independently replicated plots.

2.3.2. Grain Weight per Spike, 1000-Grain Weight and Grain Yield

Grain yield and its related traits were recorded from an average of two 2 m^2 harvest areas in the middle of each plot. All spikes were manually harvested, threshed and weighed. The average grain weight per spike was estimated from 30 spikes. The average weight of grains obtained from the two 2 m^2 harvest areas was converted to kg/ha. One thousand (1000) random grains from each harvested grain were weighed and recorded as 1000-grain weight after the grain moisture was monitored and measured using a grain analyzer (Infratec™, Foss, Denmark). The 1000-grain weight and grain yield were adjusted to 13% moisture. The same procedures were repeated for grains from each of the three replicates.

2.4. Statistical Analyses

The data recorded in this study were collated, cleaned and formatted in Microsoft Excel, 2018 version (Microsoft Corporation, 2018; Washington, DC, USA). At the beginning, all datasets were tested according to the basic assumptions of analysis of variance (ANOVA) at a 95% confidence interval. In addition, the normality distribution between the grain yield and soil properties was carried out using the Shapiro–Wilk test. Treatment combinations (T1–T12) were finally subjected to a one-way ANOVA, and post hoc mean separation was performed using the Tukey method with 95% confidence interval in R (version 4.2.2), with the *agricolae* package [46]. Bar graphs with means ± standard error of means were generated in GraphPad Prism, version 8.0.1 (GraphPad Software, San Diego, CA, USA). In addition, the effect of soil physicochemical properties at BF, JT and MT on grain yield was analyzed using the *lm* package in R [47,48].

3. Results

3.1. Changes in Soil Physiochemical Properties Due to Straw Return and N Fertilizer

3.1.1. Nitrogen Content in the Soil before Seeding, and at Both Jointing and Maturation Stages of Wheat

Soil N differed significantly ($p \leq 0.05$) among the 12 treatments in the two seasons (2021–2022 and 2022–2023), with the exception of JT in 2021–2022 (Table 2). The soil N at BF ranged from $0.30 \pm 0.05 - 0.56 \pm 0.11$ g N/kg in 2021–2022 and 0.24 ± 0.19 g N/kg. In addition, soil N at JT was $0.49 \pm 0.04 - 0.60 \pm 0.07$ g N/kg and $0.25 \pm 0.03 - 0.97 \pm 0.41$ g N/kg in the 2021–2022 and 2022–2023 seasons, respectively (Table 2). At MT, soil N recorded in the 2021–2022 cropping season was least for T6 (0.31 ± 0.07 g N/kg) and maximum for T8 (0.87 ± 0.03 g N/kg), while in the 2022–2023 season, the least soil N (0.35 ± 0.09 g N/kg) was recorded for T1 and T9 and the maximum (0.59 ± 0.15 g N/kg) for T2 (Table 2). The level of significant variation suggests that the inclusion of rice–wheat straw as crop residue, together N fertilization, altered the N content in the soil. For example, T8 (70% N rate combined with 50% SR) and T11 (100% N rate combined with 50% SR) had the highest and statistically similar soil N content, of 0.87 ± 0.03 and 0.86 ± 0.06 g N/kg, respectively (Table 2). Surprisingly, in the 2022–2023 cropping season, T2 plots which had only 50% SR retained 0.59 ± 0.15 g N/kg in the soil at MT, which was statistically different from the only-T1 plots (thus no N and SR) and the T9 plots (70% N and 100% SR) (Table 2).

Table 2. Influence of combined used of nitrogen fertilizer and rice-straw return rates on soil nitrogen content (g/kg) under winter wheat cultivation in 2021–2022 and 2022–2023 seasons.

Treatments	2021–2022			2022–2023		
	BF	JT	MT	BF	JT	MT
T1	0.45 ± 0.00 $^{a–c}$	0.56 ± 0.02 ^{a}	0.45 ± 0.03 $^{c–e}$	0.34 ± 0.09 $^{b–d}$	0.41 ± 0.14 ^{cd}	0.35 ± 0.09 ^{b}
T2	0.56 ± 0.11 ^{a}	0.48 ± 0.05 ^{a}	0.43 ± 0.06 $^{c–e}$	0.44 ± 0.01 $^{a–d}$	0.48 ± 0.08 ^{cd}	0.59 ± 0.15 ^{a}
T3	0.50 ± 0.05 ^{ab}	0.59 ± 0.06 ^{a}	0.45 ± 0.05 $^{c–e}$	0.41 ± 0.03 $^{a–d}$	0.42 ± 0.13 ^{cd}	0.44 ± 0.00 ^{ab}
T4	0.53 ± 0.08 ^{a}	0.50 ± 0.04 ^{a}	0.41 ± 0.03 $^{d–f}$	0.61 ± 0.18 ^{a}	0.72 ± 0.17 ^{b}	0.42 ± 0.03 ^{ab}
T5	0.35 ± 0.10 ^{bc}	0.49 ± 0.04 ^{a}	0.72 ± 0.11 ^{b}	0.38 ± 0.05 $^{a–d}$	0.51 ± 0.05 ^{cd}	0.49 ± 0.04 ^{ab}
T6	0.53 ± 0.08 ^{a}	0.49 ± 0.05 ^{a}	0.31 ± 0.07 ^{f}	0.51 ± 0.07 $^{a–c}$	0.35 ± 0.02 ^{de}	0.44 ± 0.01 ^{ab}
T7	0.41 ± 0.04 $^{a–c}$	0.49 ± 0.04 ^{a}	0.52 ± 0.07 ^{c}	0.30 ± 0.13 ^{cd}	0.97 ± 0.41 ^{a}	0.51 ± 0.07 ^{ab}
T8	0.30 ± 0.05 ^{c}	0.68 ± 0.14 ^{a}	0.87 ± 0.03 ^{a}	0.41 ± 0.02 $^{a–d}$	0.69 ± 0.13 ^{b}	0.45 ± 0.01 ^{ab}
T9	0.56 ± 0.11 ^{a}	0.50 ± 0.03 ^{a}	0.42 ± 0.02 $^{c–e}$	0.56 ± 0.13 ^{ab}	0.25 ± 0.03 ^{e}	0.35 ± 0.09 ^{b}
T10	0.39 ± 0.06 $^{a–c}$	0.60 ± 0.07 ^{a}	0.36 ± 0.05 ^{ef}	0.24 ± 0.19 ^{d}	0.96 ± 0.04 ^{a}	0.37 ± 0.07 ^{ab}
T11	0.35 ± 0.10 ^{bc}	0.53 ± 0.00 ^{a}	0.86 ± 0.06 ^{a}	0.38 ± 0.06 $^{a–d}$	0.51 ± 0.04 ^{c}	0.54 ± 0.10 ^{ab}
T12	0.49 ± 0.04 ^{ab}	0.51 ± 0.03 ^{a}	0.49 ± 0.09 ^{cd}	0.60 ± 0.17 ^{a}	0.38 ± 0.02 $^{c–e}$	0.37 ± 0.07 ^{ab}

Three stages of soil sampling comprised before seeding (BF), jointing stage (JT) and maturation stage (MT). Treatments comprised 0 kg N /ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46%N) was applied in proportion at sowing, wintering, and jointing stages. Means from three replications and independent plots and their standard errors of mean (SEM) at each soil sampling stage are shown in a column. Mean ± SEM in a column with the same column with a common letter indicate no significant difference ($p > 0.05$), while those with no common alphabet indicate significant difference ($p \leq 0.05$) using Tukey's post hoc mean separation.

3.1.2. Soil Nitrate Level before Seeding, and at Both Jointing and Maturation Stages of Winter Wheat under N Fertilization and Straw Return

The soil NO_3^- levels varied significantly ($p \leq 0.05$) in the two winter wheat-cropping seasons at BF, JT and MT in both seasons (Figure 3A,B). In year one (2021–2022), T7 (70% N and no SR) had the highest amount (23.95 ± 1.61 g NO_3^-/kg), and this was different from only T8 (20.96 ± 1.38 g NO_3^-/kg) and T9 (20.60 ± 1.74 g NO_3^-/kg) (Figure 3A) at BF; however the NO_3^- recorded on the T9 plot differed significantly from only T6 and T11 (Figure 3A). At JT, soil NO_3^- was highest (22.90 ± 2.45 g NO_3^-/kg) on the T5 plot (33.30% N and 50% SR) but was not different from T4 and T10, indicating that integrated use of N fertilization and crop residue could make N in the form of NO_3 available to plants in almost the way as N synthetic fertilizer. Likewise, at MT, the maximum NO_3 (13.96 ± 0.93 g NO_3^-/kg) was obtained from the plots treated with T8, and this was not statistically different from other treatments, except T3 (Figure 3A).

On the other hand, the NO_3 levels in the second year of cropping (2022–2023) were mostly lowest on the plots treated with no N or no SR (Figure 3B). For instance, T1, T4, T7 and T10 had 14.00 ± 5.40 − 14.64 ± 4.76 g NO_3^-/kg, and these were lower and different from those recorded on plots that received both N fertilization and SR (19.38 ± 0.02 − 23.66 ± 4.26 g NO_3^-/kg) at BF. These indicate that the inclusion of rice–wheat straw combined with N fertilizer allows the retention of a significant amount of soil NO_3^- reserves, as was the case at both JT and MT (Figure 3B).

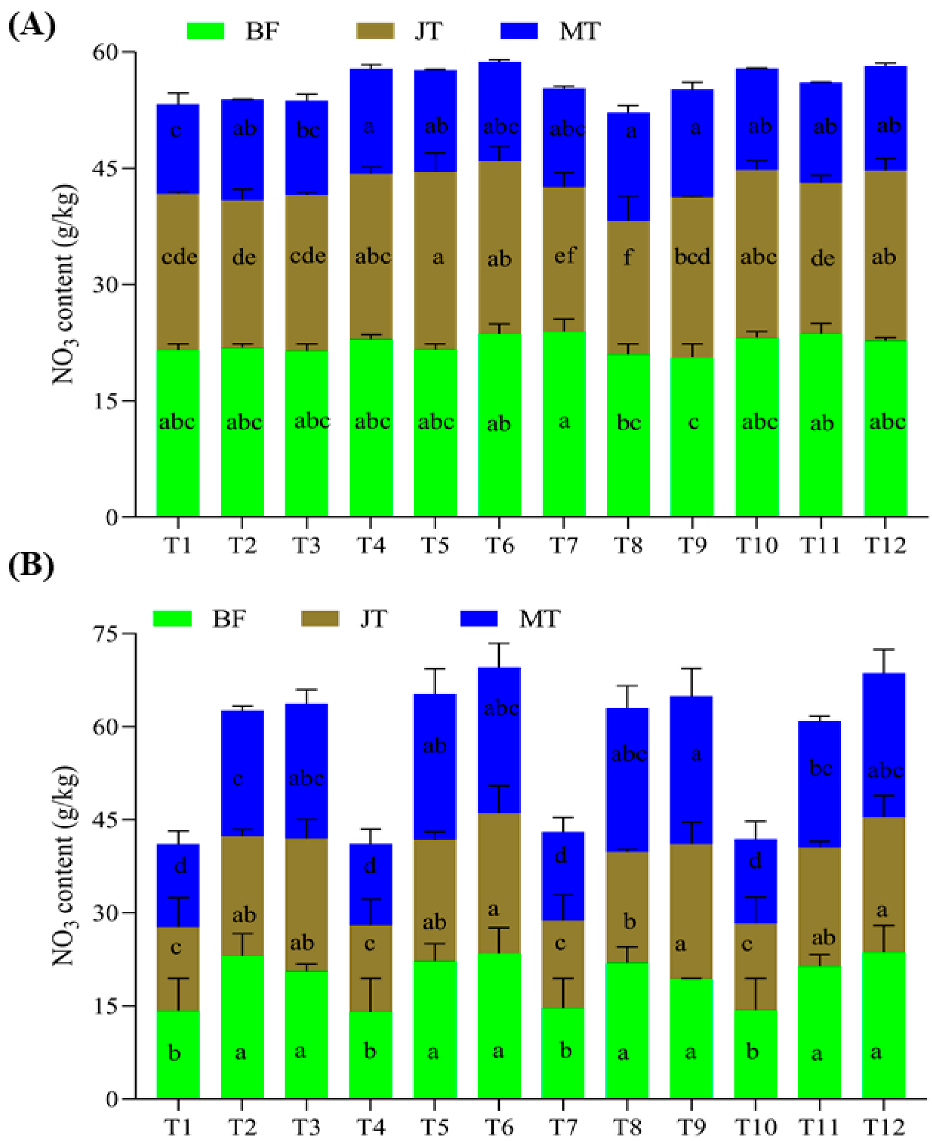

Figure 3. Soil nitrate (NO_3) levels as affected by combined application of straw return (SR) and nitrogen fertilizer rates of winter wheat grown in 2021–2022 season (**A**), and 2022–2023 season (**B**) before seeding (BF, green portion) and at jointing stage (JT, brown portion) and maturation stage (MT, blue portion). Treatments comprised 0 kg N /ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Columns represent means from three replications and independent plots. The error bars represent standard error of means. Bars with the same color with a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation [4,16,19,32,49].

3.1.3. Content of Soil Ammonium in Rice–Wheat Rotation Fields with Different N Fertilization and Straw Return

The level of soil NH_4^+ differed significantly in the 2021–2022 winter wheat-cropping season at BF, JT and MT (Figure 4A). The highest content of soil NH_4^+ was recorded in plots treated with T10 (4.99 ± 0.17 g NH_4^+/kg), which was not different from those recorded for T4, T5, T6, and T9 at BF (Figure 4A). Similarly, at JT, T5 had 1.02 ± 0.13 g NH_4^+/kg of soil, which was statistically similar to plots treated with only 50% and 100% rice–wheat straw returned (Figure 4A). Plots treated with T5 retained soil NH_4^+ at the level of

4.99 ± 0.67 g NH_4^+/kg soil, and this was not different from T6 (3.84 ± 0.53 g NH_4^+/kg soil), T11 (3.90 ± 0.19 g NH_4^+/kg soil) and T12 (4.54 ± 0.13 g NH_4^+/kg soil) at MT.

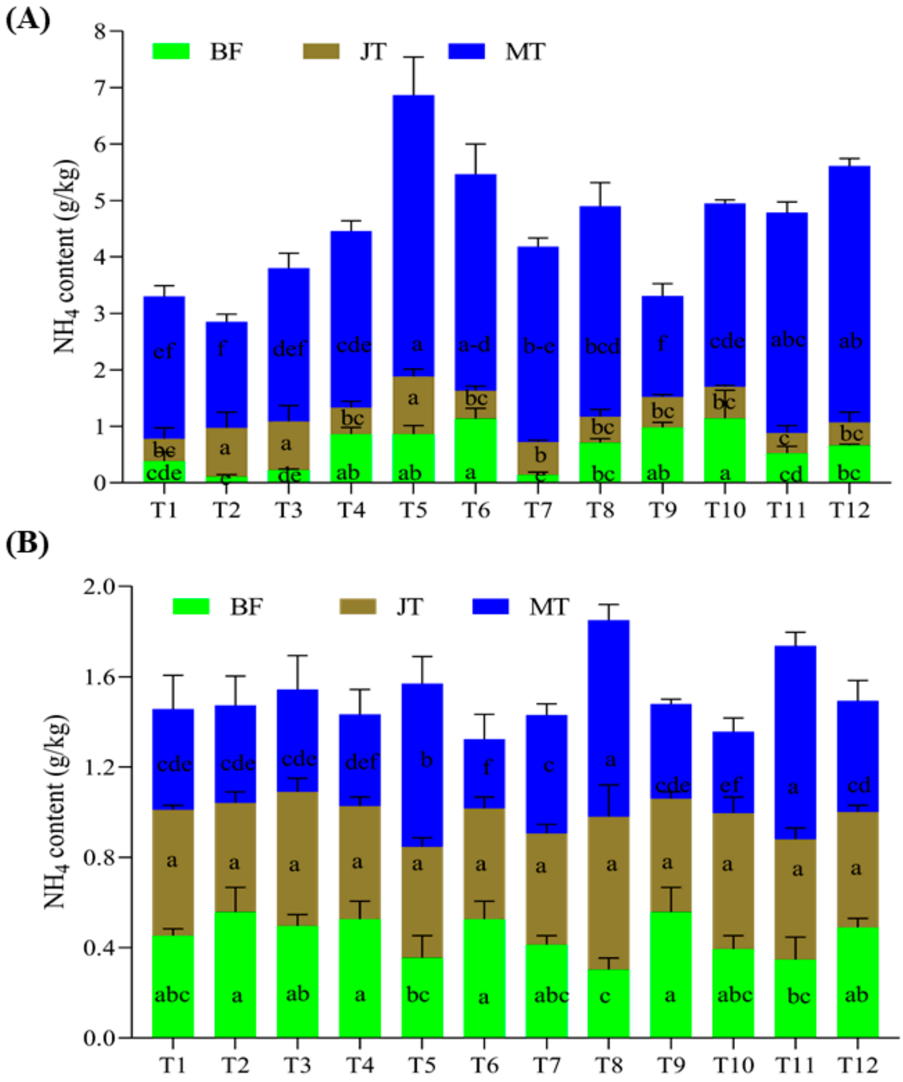

Figure 4. Soil ammonium (NH_4) levels as affected by combined application of straw return (SR) and nitrogen fertilization levels on winter wheat grown in 2021–2022 season (**A**), and 2022–2023 season (**B**) before seeding (BF, green portion), and at jointing stage (JT, brown portion) and maturation stage (MT, blue portion). Treatments comprised 0 kg N/ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Columns represent means from three replications and independent plots. The error bars represent standard error of means. Bars with the same color with a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation.

In the 2022–2023 winter wheat-cropping season, the soil NH_4^+ differed significantly ($p \leq 0.05$) at BF and MT (Figure 3B). At BF, the maximum level of soil NH_4^+ (0.56 ± 0.11 g NH_4^+/kg soil) was recorded for plots treated with T2 and T9, which were not different from those recorded by T3, T4, T6, T9 and T10 (Figure 4B), while at MT, the highest soil NH_4^+ (0.87 ± 0.07 and 0.86 ± 0.06 g NH_4^+/kg soil) was recorded for the T8 and T11 plots, respectively; these were followed by T5 (0.72 ± 0.12 g NH_4^+/kg soil).

Overall, the above results on soil N, NO_3^- and NH_4^+ largely suggest that the incorporation of crop residues improves the availability and accessibility of soil N, as well as its usable forms (NO_3^- and NH_4^+), to plant roots.

3.1.4. Variation in Soil Phosphorus in Wheat Fields before Seeding and at Both Jointing and Maturation Stages as Affected by Rice Straw Return and N Fertilization

Straw return is reported to provide more available phosphorus (P) than mineral fertilization [19]. This, according to Kubar et al. [6], may enhance plant P uptake because of the straw effect on the activity of P with low solubility. With this in mind, we quantified the P content in the soil at three stages (ST, JT and MT) in both the 2021–2022 and 2022–2023 winter wheat-cropping seasons (Table 3). The maximum soil P (71.70 ± 14.26 mg P/kg) was recorded for plots treated with T9 at BF, while 70.50 ± 9.28 mg P/kg was obtained from plots treated with T5 at JT and 72.13 ± 15.53 mg P/kg at MT, all in the 2021–2022 season (Table 1). In the same way, the T8 and T5 plots had the maximum P levels at BF (62.49 ± 2.50 mg P/kg) and JT (70.17 ± 14.90 mg P/kg) (Table 3). Surprisingly, the highest P content was recorded for plots treated with T10, which was not different from plots treated with the combined use of N and SR (Table 3). This highlights the fact that incorporation of crop residues, together with N fertilization, could enhance the availability of P in the soil matrix [37].

Table 3. Impact of nitrogen fertilizer and rice straw return rates on soil phosphorus content (mg/kg) under winter wheat cultivation in 2021–2022 and 2022–2023 seasons.

Treatments	2021–2022			2022–2023		
	BF	JT	MT	BF	JT	MT
T1	61.83 ± 4.39 ^{ab}	60.50 ± 0.02 ^{bc}	49.23 ± 7.37 ^{ef}	47.43 ± 7.40 ^{bc}	43.36 ± 12.00 ^{d}	57.70 ± 5.60 ^{cd}
T2	44.93 ± 12.51 ^{d}	58.63 ± 2.59 ^{bc}	72.13 ± 15.53 ^{a}	61.71 ± 1.70 ^{a}	56.048 ± 0.70 ^{bc}	59.72 ± 3.60 $^{a–d}$
T3	60.20 ± 2.76 ^{bc}	60.40 ± 0.82 ^{bc}	54.90 ± 1.70 ^{de}	56.50 ± 6.50 ^{ab}	43.62 ± 11.70 ^{d}	59.71 ± 3.60 $^{a–d}$
T4	57.57 ± 0.12 ^{bc}	60.93 ± 0.29 ^{bc}	49.00 ± 7.60 ^{ef}	52.65 ± 2.60 ^{abc}	51.92 ± 3.40 ^{bcd}	63.73 ± 0.50 $^{a–d}$
T5	56.67 ± 0.78 ^{bc}	70.50 ± 9.28 ^{a}	43.87 ± 12.74 ^{f}	52.22 ± 2.20 ^{abc}	70.17 ± 14.90 ^{a}	64.18 ± 0.90 $^{a–d}$
T6	56.93 ± 0.51 ^{bc}	55.97 ± 5.25 ^{c}	45.60 ± 11.00 ^{f}	56.89 ± 6.90 ^{ab}	54.84 ± 0.50 ^{bcd}	57.31 ± 6.00 ^{cd}
T7	59.50 ± 2.06 ^{bc}	65.53 ± 4.3 ^{ab}	58.60 ± 2.00 ^{cd}	48.79 ± 8.80 ^{abc}	55.45 ± 0.11 ^{bcd}	72.05 ± 8.80 ^{ab}
T8	49.57 ± 7.88 ^{cd}	64.53 ± 4.3 ^{ab}	62.60 ± 6.00 ^{bc}	62.49 ± 2.50 ^{a}	60.97 ± 5.70 ^{abc}	67.58 ± 4.30 ^{abc}
T9	71.70 ± 14.26 ^{a}	58.77 ± 2.45 ^{bc}	65.63 ± 9.03 ^{b}	53.42 ± 3.40 ^{abc}	49.36 ± 5.90 ^{cd}	72.80 ± 9.50 ^{ab}
T10	59.50 ± 2.06 ^{bc}	59.87 ± 1.35 ^{bc}	62.30 ± 5.70 ^{bc}	41.85 ± 1.90 ^{c}	54.20 ± 1.10 ^{bcd}	73.18 ± 9.90 ^{a}
T11	58.83 ± 1.39 ^{bc}	59.97 ± 1.25 ^{bc}	57.97 ± 1.36 ^{cd}	54.02 ± 5.40 ^{abc}	62.40 ± 7.10 ^{ab}	59.34 ± 3.90 ^{bcd}
T12	55.17 ± 2.28 ^{bcd}	59.03 ± 2.19 ^{bc}	57.40 ± 0.80 ^{cd}	60.25 ± 6.30 ^{ab}	61.36 ± 6.10 ^{abc}	51.98 ± 11.30 ^{d}

Three stages of soil sampling comprised before seeding (BF), jointing (JT) and maturation stages (MT). Treatments comprised 0 kg N/ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1)0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Means from three replicated independent plots and their standard errors of mean (SEM) at each soil sampling stage are shown in the columns. Mean ± SEM in a column with a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation.

3.1.5. Changes in K Content in Winter Wheat Fields before Seeding and at Both Jointing and Maturation Stages as Influenced by Rice–Wheat Straw Return and N Fertilization

The available K in the soil differed significantly ($p \leq 0.05$) across BF, JT and MT due to the integrated use of rice–wheat straw return and N fertilizer in the 2021–2022 and 2022–2023 seasons (Figure 5A,B). In the 2021–2022 season, the maximum amount of soil K was (203.50 ± 29.40 mg/kg) at BF, and this statistically differed from only T1, T2 and T11 (Figure 5A). At JT, plots treated with T6 had the maximum soil K (191.80 ± 10.99 mg/kg), and this was not different from T2, T5, T8, T10 and T11 (186.20 ± 4.99 − 191.40 ± 10.19 mg/kg), whereas at MT, T1 and T2 had statistically similar but higher soil K levels of 157.40 ± 24.50 and 149.50 ± 27.00 mg/kg, respectively, and these were different from the other treatments (Figure 5A).

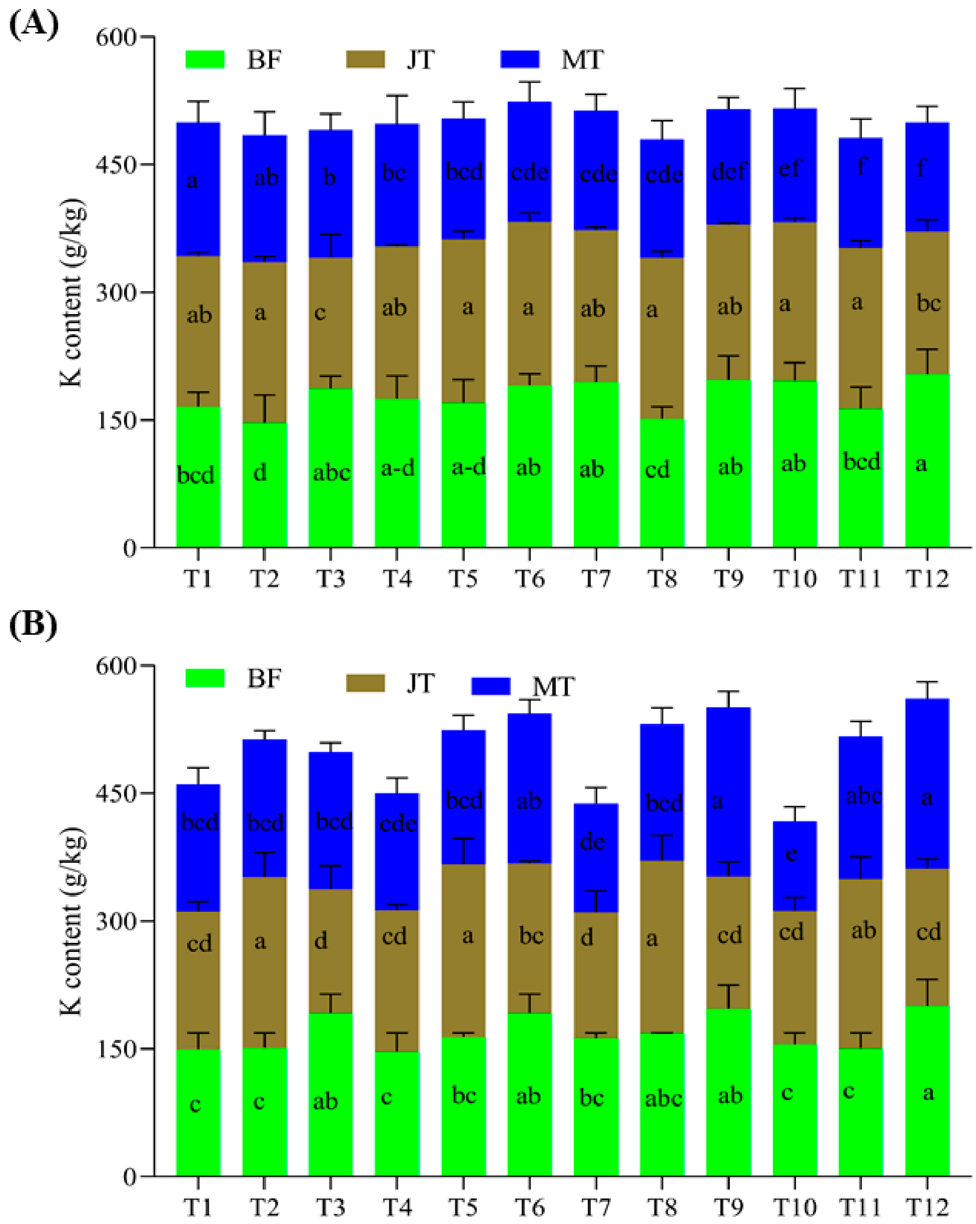

Figure 5. Soil potassium (K) levels as affected by combined application of straw return (SR) and nitrogen fertilization on winter wheat grown in 2021–2022 season (**A**), and 2022–2023 season (**B**) before seeding (BF, green portion), and at jointing stage (JT, brown portion) and maturation stage (MT, blue portion). Treatments comprised 0 kg N/ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Columns represent means from three replicated independent plots. The error bars represent standard error of means. Bars with the same color with a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation.

Interestingly, in 2022–2023, the plots treated with both N fertilization and rice–wheat straws or only rice–wheat straws had maximum amount of soil K (Figure 5B). Specifically, at BF, T12 plots had highest level of soil K (of 200.20 ± 31.10 mg/kg), while T5 and T12 had 202.70 ± 29.90 and 199.40 ± 19.40 mg/kg, respectively, which were the highest in JT and

MT. All these results suggest that inclusion of rice–wheat straw with N fertilization could enhance K supply and balance in the soil for sustainable wheat production.

3.1.6. Impact of Combined Use of Rice–Wheat Straw Return and N Fertilization on Soil pH and Moisture Content in Winter Wheat-Growing Seasons

The soil pH varied significantly ($p \leq 0.05$) due to the combined effect of SR and N fertilization at BF, JT and MT in only the 2021–2022 winter wheat-cropping season (Table 4). The pH content of soils at BF ranged from 7.47 ± 0.10 − 7.87 ± 0.09, with 7.43 ± 0.09 − 7.70 ± 0.06 and 7.13 ± 0.17 − 7.53 ± 0.23 at JT and MT (Table 4). These results indicate that soil pH (alkalinity) reduced marginally due to the integrated use of crop residues and N fertilization.

Table 4. Effect of nitrogen fertilization and rice straw return on soil pH in winter wheat cultivation during 2021–2022 and 2022–2023 seasons.

Treatments	2021–2022			2022–2023		
	BF	JT	MT	BF	JT	MT
T1	7.67 ± 0.02 [a–c]	7.70 ± 0.06 [a]	7.33 ± 0.03 [a–c]	7.47 ± 0.04 [a]	7.53 ± 0.02 [a]	7.43 ± 0.04 [a]
T2	7.70 ± 0.01 [ab]	7.55 ± 0.08 [b–d]	7.13 ± 0.17 [c]	7.50 ± 0.01 [a]	7.67 ± 0.11 [a]	7.57 ± 0.09 [a]
T3	7.60 ± 0.02 [bc]	7.60 ± 0.20 [a–c]	7.53 ± 0.23 [a]	7.53 ± 0.02 [a]	7.60 ± 0.04 [a]	7.53 ± 0.06 [a]
T4	7.47 ± 0.10 [c]	7.53 ± 0.08 [b–d]	7.20 ± 0.11 [bc]	7.33 ± 0.18 [a]	7.63 ± 0.08 [a]	7.37 ± 0.11 [a]
T5	7.67 ± 0.09 [a–c]	7.50 ± 0.05 [cd]	7.20 ± 0.11 [bc]	7.53 ± 0.02 [a]	7.57 ± 0.01 [a]	7.43 ± 0.04 [a]
T6	7.83 ± 0.05 [a]	7.43 ± 0.04 [d]	7.30 ± 0.01 [a–c]	7.63 ± 0.12 [a]	7.47 ± 0.09 [a]	7.40 ± 0.07 [a]
T7	7.57 ± 0.15 [ab]	7.63 ± 0.11 [ab]	7.33 ± 0.03 [a–c]	7.60 ± 0.09 [a]	7.60 ± 0.04 [a]	7.50 ± 0.03 [a]
T8	7.73 ± 0.05 [ab]	7.43 ± 0.09 [d]	7.40 ± 0.09 [ab]	7.63 ± 0.12 [a]	7.43 ± 0.12 [a]	7.40 ± 0.07 [a]
T9	7.70 ± 0.16 [ab]	7.60 ± 0.07 [abc]	7.33 ± 0.03 [a–c]	7.50 ± 0.01 [a]	7.50 ± 0.06 [a]	7.50 ± 0.03 [a]
T10	7.57 ± 0.02 [bc]	7.67 ± 0.06 [a]	7.37 ± 0.06 [a–c]	7.33 ± 0.18 [a]	7.60 ± 0.04 [a]	7.43 ± 0.04 [a]
T11	7.87 ± 0.09 [a]	7.43 ± 0.11 [d]	7.13 ± 0.17 [c]	7.53 ± 0.02 [a]	7.53 ± 0.02 [a]	7.57 ± 0.09 [a]
T12	7.73 ± 0.06 [ab]	7.67 ± 0.05 [a]	7.40 ± 0.09 [ab]	7.53 ± 0.02 [a]	7.53 ± 0.02 [a]	7.53 ± 0.06 [a]

Three stages of soil sampling comprised before seeding (BF), jointing stage (JT) and maturation stage (MT). Treatments comprised 0 kg N /ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Means from three replicated independent plots and their standard errors of mean (SEM) at each soil sampling stage are shown in the columns. Mean ± SEM in a column with a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation.

The combined effect of SR and N fertilizer rates was significant ($p \leq 0.05$) on soil moisture recorded at only BF and JT in both the 2021–2022 and 2022–2023 seasons (Figure 6A,B). The highest range of soil moisture was recorded for T1 and T2 (30.03 ± 2.07 − 34.40 ± 2.15%) at BF in 2021–2022, while 26.43 ± 0.38 − 30.52 ± 3.54% were recorded for nine treatments, with the exception of T2, T3 and T11 at JT (Figure 6A). At BF in 2022–2023, soils treated with N and rice–wheat largely had high moisture contents (Figure 6B). However in the same season, there were some discrepancies in soil moisture recorded at JT (Figure 5B) [18,26].

3.2. Effect of Combined Use of Rice Straw and N Fertilization on Wheat Grain Yield

Wheat grain yield is influenced by a number of components, including grain weight per spike and 1000-grain weight [5,6]. Grain weight per spike, 1000-grain weight and grain yield differed significantly ($p \leq 0.05$) among the treatments in both the 2021–2022 and 2022–2023 seasons (Figure 7A–C). The highest grain weight of 63.00 ± 10.83 g per spike was obtained from T2, which was not different from T3 (62.33 ± 10.17 g), T10 (58.33 ± 6.17 g) and T12 (57.33 ± 5.17 g) in 2021–2022 (Figure 6A), while in 2022–2023, the highest grain weight of 49.71 ± 12.60 g per spike was produced by plots treated with either T7 or T9 (Figure 7A).

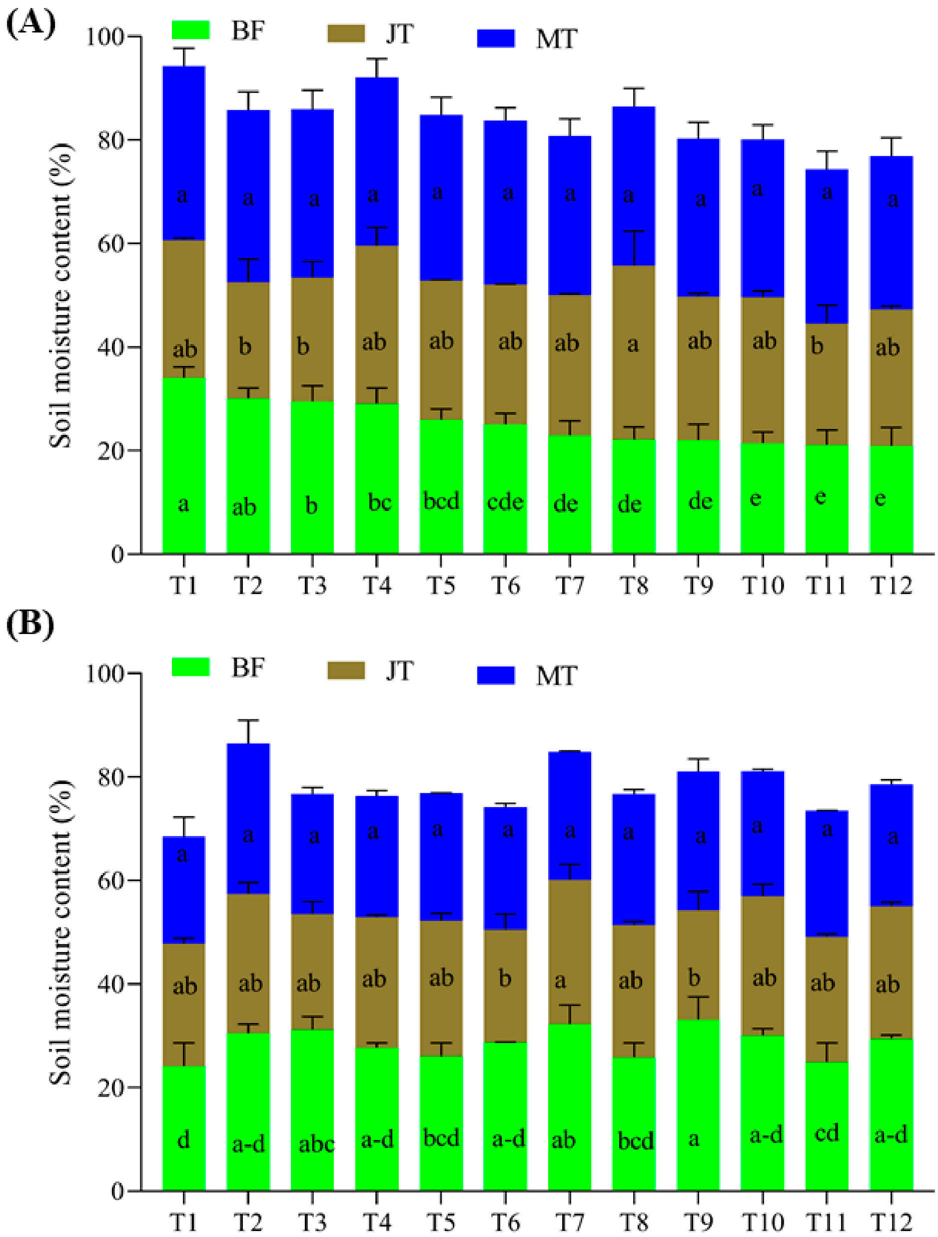

Figure 6. Soil moisture content (%) as influenced by combined application of straw return (SR) and nitrogen fertilization on winter wheat grown in 2021–2022 season (**A**), and 2022–2023 season (**B**) before seeding (BF, green portion), and at jointing stage (JT, brown portion) and maturation stage (MT, blue portion). Treatments comprised 0 kg N/ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Columns represent means from three replicated independent plots. The error bars represent standard errors of means. Bars with the same color and a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation.

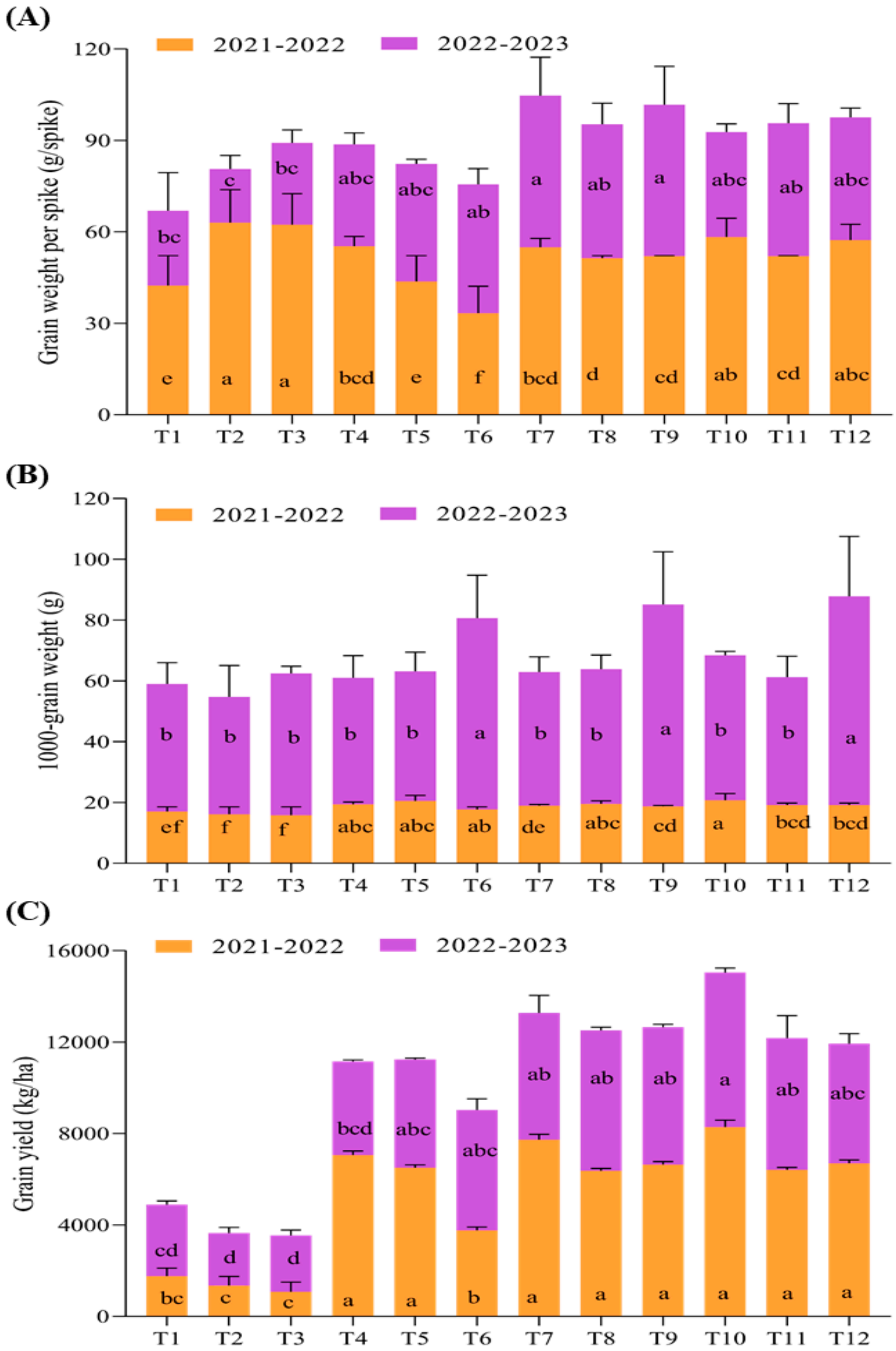

Figure 7. Influence of integrated use of nitrogen fertilizer and rice straw return (SR) on grain weight per spike (**A**), 1000-grain weight (**B**) and grain yield (**C**) of winter wheat grown in 2021–2022 and 2022–2023 seasons. Treatments comprised 0 kg N/ha with 0% SR (T1), 50% SR (T2) and T3 (100% SR); 33.3% N applied with 0% SR (T4), 50% SR (T5) and T6 (100% SR); 70% N applied with 0% SR (T7), 50% SR (T8) and T9 (100% SR); and 100% N applied with 0% SR (T1) 0, 50% SR (T11) and T12 (100% SR). The nitrogen rate (180 kg N/ha of urea with 46% N) was applied in proportion at sowing, wintering, and jointing stages. Columns represent means from three replicated independent plots. The error bars represent standard errors of means. Bars with the same color and a common letter indicate no significant difference ($p > 0.05$), while those with no common letter indicate significant difference ($p \leq 0.05$), using Tukey's post hoc mean separation.

The highest 1000-grain weight of 20.77 ± 2.18 g was obtained from plots treated with T10 followed by T5 (20.27 ± 1.88 g), T8 (19.57 ± 0.98 g) and T4 (19.37 ± 0.78 g); of these, none was statistically different from the other in the 2021–2022 season (Figure 7B), while in the 2022–2023 season, T6, T9 and T12 treatments resulted in a statistically similar 1000-grain weight, ranging from 63.00 ± 14.03 to 68.67 ± 19.69 g, and these treatments were different from the other treatments (Figure 7B).

With regard to grain yield, T4, T5 and T7–T12 plots produced $6337 \pm 133 - 8299 \pm 298$ kg/ha, of which neither was statistically different from T1, T2, T3 and T6 ($1079 \pm 422 - 3760 \pm 154$ kg/ha) (Figure 7C). Also, in the 2022–2023 season, T5–T12 treatments produced $4726.00 \pm 62 - 6758 \pm 196$ kg of grains per ha (Figure 6C). These results suggest that the combined use of straw return and N fertilization results in improved grain yield and its components (grain weight per ear and 1000-grain weight) (Figure 7A–C).

We also conducted regression analyses to assess the impact of the soil physicochemical properties at BF, JT and MT on grain yield of winter wheat at three stages (Figures 8 and 9). The studied soil properties had diverse effects on grain yield ($p \leq 0.05$). In the 2021–2022 cropping season for instance, the soil N at BF had a 37% reduction in grain yield, while the soil moisture at MT also reduced the grain yield by 34% (Figure 8). On the contrary, soil NH_4 at BF and MT had a 49 and 44% increase in grain yield, respectively (Figure 8). Also, soil NO_3 and P contents resulted in a 57 and 66% rise in grain yield. In the 2022–2023 winter season, soil NH_4 and P levels at JT led to a rise of 34 and 35% in grain yield, respectively (Figure 9). In addition, soil P level resulted in a 47% rise in grain yield at MT (Figure 9). Strikingly, soil pH at JT resulted in a 40% decline in grain yield (Figure 9). Altogether, these results add to the extensive literature on the effect of soil nutrient abundance on wheat grain yield.

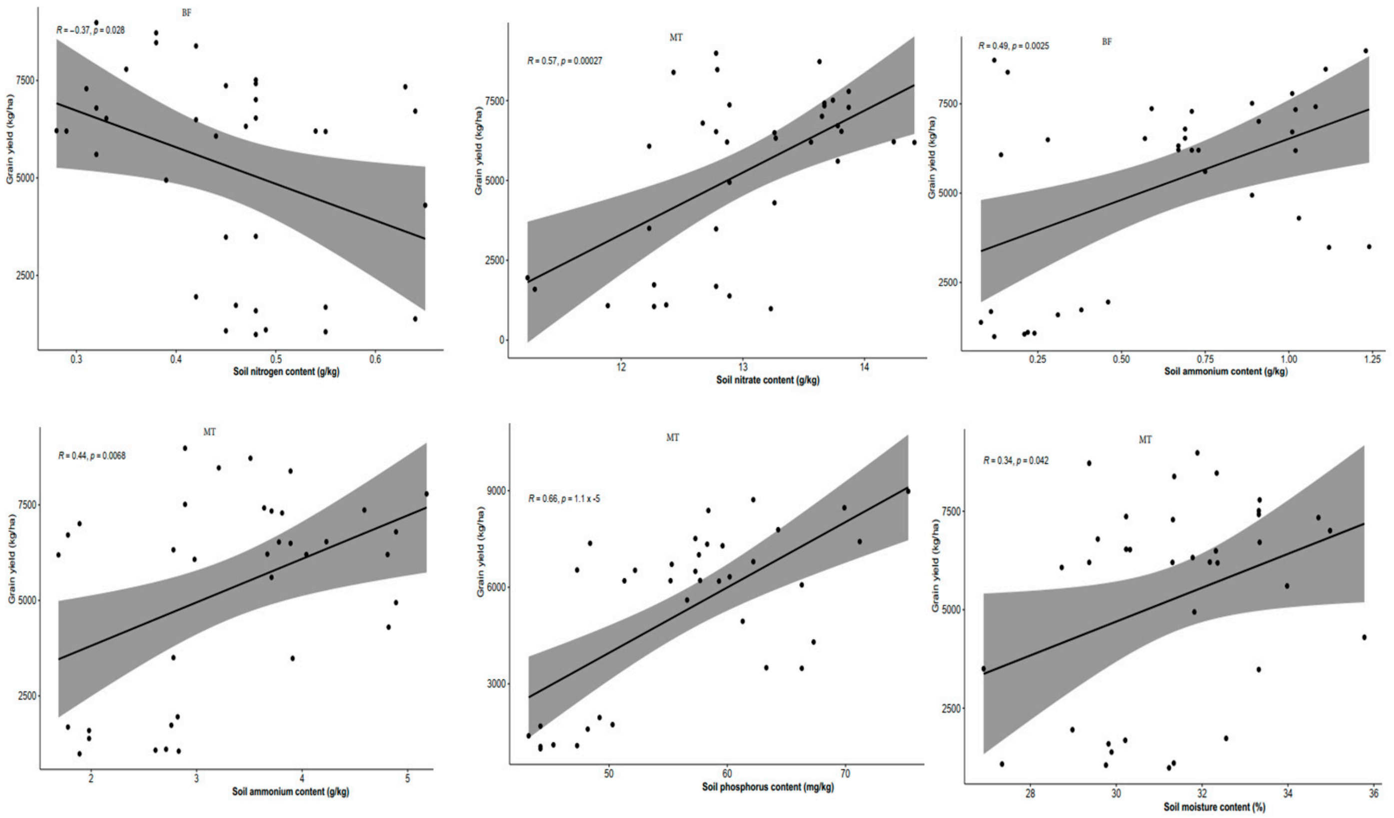

Figure 8. Soil physicochemical properties with significant ($p \leq 0.05$) effect on grain yield of winter wheat cultivated in 2021–2022 season. The three stages of soil samples used for analyses are shown at the top of each figure: before seeding (BF), jointing stage (JT) and maturation stage (MT). The R-value on each figure represents variation in grain yield explained by each of the soil physicochemical properties.

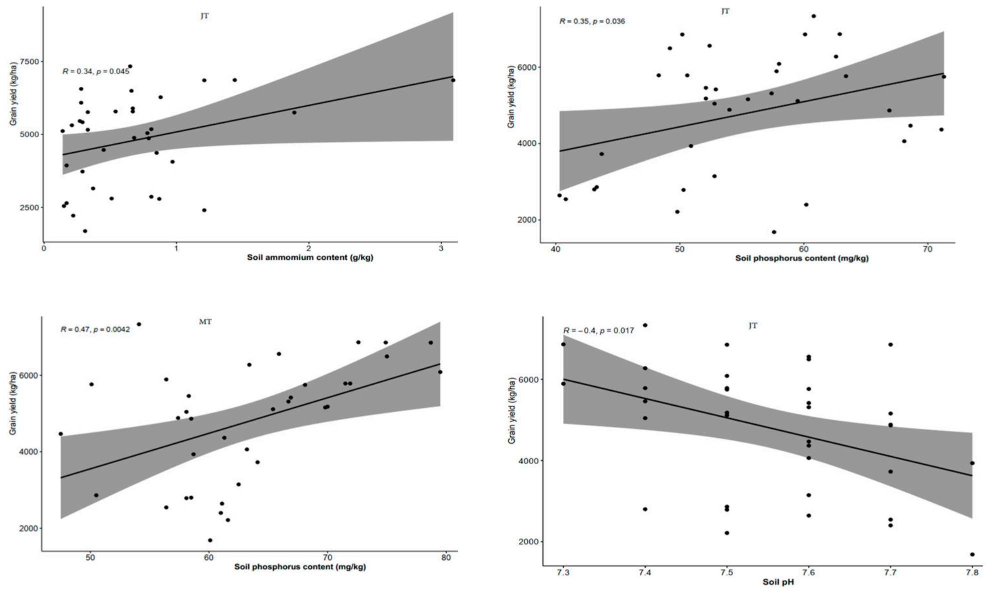

Figure 9. Soil physicochemical properties with significant ($p \leq 0.05$) effect on grain yield of winter wheat cultivated in 2022–2023 season. The three stages of soil samples used for analyses are shown at the top of each figure: jointing stage (JT) and maturation stage (MT). The R-value on each figure represents variation in grain yield explained by each of the soil physicochemical properties.

4. Discussion

Globally, the predominant approach for managing crop straw is through the practice of straw returning (SR). Nevertheless, the prevalent practice of SR in the contemporary rice–wheat rotation system has been found to have detrimental impacts on soil fertility and crop yield [44,45]. This study presents findings that support the notion that incorporating rice straw at a rate of 50 and 100% straw return kg/ha with 33.3, 70 and 100% N fertilization and topdressing application rates in the rice–wheat rotation system has a positive impact on the soil physicochemical properties and wheat productivity, ultimately leading to enhanced wheat grain yields. The traditional practice of incorporating straw into the field has the potential to rapidly enhance soil health and fertility. The utilization of concentrated ditch-buried straw return for an extended period presents benefits compared to alternative methods of SR in terms of enhancing the buildup of essential nutrients and soil organic matter. The synergistic effect of minimal- or zero-tillage practices, alongside SR, contributes to soil health and overall soil fertility [26,42].

4.1. Effect of Rice Straw and N Fertilization on Soil Physicochemical Properties

The burning of straw is prohibited in China, due to its detrimental impact on the environment, including pollution and a significant increase in ground temperature. Increased temperatures have the potential to directly impair the viability of beneficial microorganisms present in soil, thereby compromising their beneficial functions [31,40]. Furthermore, these high temperatures can also have a detrimental impact on the optimal uptake of essential soil nutrients by crops, thereby potentially hindering their overall nutrient absorption capacity [4,5,18,37]. Prior meta-analysis [30] has demonstrated that nitrogen uptake is necessary to support soil microbial activities [15,19,50]. China, being a country with a long-standing history of agriculture, annually generates approximately 1.04 billion metric tonnes of crop straw [18,29,30]. Straw returning is an efficacious method which is being promoted for addressing the excessive straw generation and for mitigating the environmental pollution associated with straw burning. Previous studies have demonstrated that the practice of returning straw to the field significantly impacts on the physicochemical properties of the soil, as well as on the microbial community [3,15,41]. The findings of our study indicate that the varied rates of nitrogen application and rice straw return differentially impacted soil physicochemical properties and wheat growth at the different growth stages, and thus influenced wheat grain yield (Tables 1–3). Furthermore, it was observed that the utilization of nitrogen fertilizer with topdressing had a more favorable impact on SR in the rice–wheat crop rotation system (Figures 3–5). These findings may be ascribed to the combined effect of SR and N fertilizer application (N rate). The variation in soil nitrogen indicates that the combination of crop residue (rice straw) and synthetic nitrogen fertilizer influences the abundance of soil nitrogen, even in its usable form (nitrates) [6,13,25,26,42,51].

Crop straw is rich in essential nutrients that play a crucial role in the growth and development of plants [18,19,35]. Nevertheless, SR possesses the capacity to replenish the essential nutrients that plants may deplete as a result of intensive cultivation, imbalanced application of fertilizers, and inadequate water supply [20,50]. Our study revealed that SR application boosted accessibility of nitrogen (N), phosphorous (P), nitrates (NO_3^-), and ammonium (NH_4^+) within 20 cm soil depth (Figures 3–5). This is consistent with earlier reports by Zhang et al. [50] and Wang et al. [27]. The study revealed a significant decrease in soil phosphorus (P) availability in the SR treatment as compared to the CK treatment, specifically at depths ranging from 20 to 30 cm. This can be attributed to the incorporation of straw into the uppermost 20 cm of soil, which effectively impedes leaching of P. Xie et al. [19] reported comparable findings in a rice–wheat experiment of extended duration [52]. The process of increasing soil organic carbon (SOC) requires a comparable duration of time [9,18,22]. Nevertheless, the agronomic practice of strip tillage exhibited a significant SOC level over the duration of the two-year study. The increase in SOC can be attributed to the occurrence of more humid weather conditions, the rice–wheat crop rotation system, and the increased application of nitrogen (N) fertilizers. The acceleration of crop residue decomposition can likely be attributed to these factors [9,18].

Puddling in a rice–wheat crop rotation system, in the absence of straw incorporation, releases essential nutrients for optimal plant growth [15,16]. A substantial increase in soil moisture content was observed. The highest soil moisture was recorded for the plots treated with 50 or 100 SR at JT and MT; this is consistent with earlier reports that straw returned to the soil minimizes the evaporation rate of soil water, and enhances soil water-holding capacity and water use efficiency [18,26]. The soil exhibited a sandy loam texture, characterized by a high bulk density and a decrease in the percentage of water-stable aggregates [43]. Nevertheless, there was no significant difference observed in the soil moisture content between the two seasons. The presence of organic matter has been found to have several effects on soil properties. Firstly, it has been observed to decrease bulk density and soil compactibility [52]. Additionally, organic matter has been shown to increase porosity and infiltration rate [13,23].

Moreover, it has been found to raise soil moisture content at field capacity [12]. These effects can be attributed to the low bulk density of organic matter and its ability to enhance soil aggregate stability. In this study, it was observed that reintroducing rice straw into the field resulted in a significant reduction in soil bulk density. The study by Song et al. [52] supports the observation that a greater number of water-stable aggregates with a size larger than 0.25 mm were formed under the soil tillage regime (STR) compared to the conventional tillage regime (CK). The rapid fluctuations in soil physical characteristics can be partially ascribed to the location-specific climate and agronomic practices. The observed variations in soil pH, which were found to be statistically significant ($p \leq 0.05$), can be attributed to the combined influence of SR and nitrogen (N) fertilization during the different growth stages of wheat: BF, JT, and MT. The results suggest that the soil pH (alkalinity) experienced a slight but significant decrease when comparing wheat fields treated with crop residues and N fertilization in the BF and MT conditions.

4.2. Effect of Rice Straw and N Fertilization with Topdressing on Wheat Grain Yield

Contradictory results have been reported by previous studies about the influence of SR on crop productivity in different climatic and soil conditions [8,9,20]. Our study found that returning crop straw to the field differentially improved wheat grain yield for the two seasons (Figure 7). This finding aligns with prior studies [4,4,35,50]. The improved wheat grain yield can be attributed to various factors. Primarily, SR replenished a substantial amount of the nutrients that were depleted by the aerial components of the wheat plants. Additionally, the presence of organic matter in crop straw contributes to improved physicochemical and biological properties of the soil, resulting in increased wheat grain productivity (Figures 6 and 7). However, earlier studies have indicated that SR had no significant effect [16,25,27] or resulted in a decline in crop productivity [15,16]. This was largely ascribed to SR-induced nitrogen immobilization, resulting in decreased crop yields [16,16,27].

The study finds that the wet climate and rice–wheat crop rotation system contribute to the decomposition of straw and the release of nutrients, which help to alleviate the disadvantages of SR. Moreover, the varied nitrogen (N) fertilization rates in this study serve to prevent the occurrence of inorganic N deficiency resulting from N immobilization [32]. The results also showed a varied wheat yield over time, for both seasons. The decrease in yield observed during the experiment can be attributed to potassium deficiency. This is supported by the low initial soil potassium content and the absence of potassium fertilizer application [45,50]. Wheat is more susceptible to potassium deficiency than rice. This is because rice can uptake potassium from irrigation water and access soil P more easily when the soil is soaked [12,16].

5. Conclusions

The outcomes of SR are contingent upon various factors, including soil type, weather conditions, climate patterns, field management practices, and cropping methods. Therefore, the present study explored the incorporation of straw into soil and assessed its impact on both soil fertility indices and crop yield within a rice–wheat rotation system over a two-year period. Our study demonstrated that the complete incorporation of straw culminated in varied levels of soil nitrogen (N), phosphorus (P), nitrate (NO_3^-), ammonium (NH_4^+), potassium, moisture, pH and wheat grain yield in comparison to the control group. The combined SR and N fertilization resulted in varied improvements in the physicochemical properties of the soil, including a reduction in bulk density and an increase in water retention capacity. Thus, a combined SR and N fertilization with topdressing may be an effective approach for enhancing soil fertility and increasing wheat grain productivity in the middle–lower Yangtze River Basin.

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Data Availability Statement: All data generated and analyzed are in the Results section.

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Conflicts of Interest: The authors declare no conflict of interest.

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