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The Effects of Tillage and Straw Incorporation on Soil Organic Carbon Status, Rice Crop Productivity, and Sustainability in the Rice-Wheat Cropping System of Eastern China

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Abstract: Soil management practices are used to enhance soil organic carbon, fertility, and crop productivity around the world. However, accurate information about the appropriate amount of straw incorporation is not available, because it is generally believed that at least 30% of the soil surface should be covered by straw, which is not implemented in all field environments. Therefore, a two-year (2016–2017) field experiment was conducted to investigate the impact of different percentages of straw incorporation and tillage methods, i.e., reduced tillage (RT) and conventional tillage (CT), on crop yield, soil organic carbon (SOC), total nitrogen (TN), and soil carbon storage (SCS) in rice–wheat cropping systems, under eight treatments. The experimental results showed that the greatest reduction in soil dry bulk density (ρ_b) was found under CT with 100% straw coverage (9.79%), whereas the least reduction occurred under CT with no straw (1.31%). The mean TN concentration, soil organic matter (SOM), and soil carbon storage (SCS) were significantly higher by 0.98 g/kg, 17.07%, and 14.20%, respectively, under reduced tillage with 60% straw incorporation (RTsi$_{60}$) compared with all other treatments. Our findings demonstrate that the incorporated wheat residues resulted in the highest rice production (7.95–8.63 t/ha) under RTsi$_{60}$. We recommend the adoption of reduced tillage with 60% straw incorporation to increase rice yield, improve soil structure, and enhance TN, SOM, and SCS in paddy soil under rice-wheat rotation fields for agricultural sustainability.

Keywords: reduced and conventional tillage; dry bulk density; soil porosity; soil organic matter; total nitrogen; rice crop; agricultural sustainability

1. Introduction

The rice–wheat rotation (RWR) system is one of the oldest and most pervasive agricultural practices in Asia, occupying about 13 million hectares each year in China [1] and 0.5, 0.8, 2.2, and 10.0 million hectares in Nepal, Bangladesh, Pakistan, and India, respectively. About 42% of the total wheat and 32% of the total rice crop areas are grown in these countries every year [2]. The RWR system is extremely important for providing a stable food supply to more than 20% of the world's population [3] and maintaining the balance between sustenance supply and populace development. The Yangtze River belt in China is the leading wheat and rice crop growth area, and RWR is an essential cropping system in Eastern China [4]. The combined field area for rice and wheat was approximately 20.1% of the total cultivation area in 2011, producing about 22.1% of the overall national grain yield in China for both crops [5]. Moreover, studies have reported that an approximate 2% increase in yield was seen in rice and wheat crop from 1970 to 1990. Since then, yield has declined due to the deteriorating natural resource base; soil degradation; the rising cost of cultivation; soil erosion; reduced aggregation; environmental pollution [6]; increasing soil organic carbon (SOC) loss; pesticide management; and long-term conventional practices such as crop-intensive tillage, plowing, residue removal or burning, decreased profit, the prolonged time involved in seedbed preparation [7], and reduced support for public agricultural research [8]. Additionally, this system requires the high use of agricultural machinery, such as moldboard plow and rotary cultivators, and aggravates the degradation of existing SOC. Thus, investigating the effects of sustainable soil management practices on soil structure and function on crop yields for agricultural sustainability in the rice-wheat cropping system is necessary [8]. Sustainability is related to soil quality, which is defined as the ability of a particular kind of soil to work, within natural or managed boundaries, to sustain animal and plant productivity, maintain or increase air and water quality, and support human health and habitation [9].

Sustainable soil management through conservation agricultural practices, including reduced tillage (RT) or no-tillage methods with straw incorporation, are becoming economically and ecologically more viable. RT allows farmers to enhance soil quality for better crop production and minimize agricultural soil carbon (C) losses [10] and soil disturbance, and provide more favorable soil conditions for crop growth [11], increased profits, and food security. Conventional tillage (CT) is the dominant tillage practice in traditional farming and has considerably contributed to China's crop production. CT involves numerous stages prior to crop sowing, such as residue removal or burning, plow tillage (PT), harrowing, and land leveling. CT can influence the physicochemical and biological properties of soil, affecting soil productivity and sustainability [12]. Long-term soil disturbance by inversion tillage or intensive CT during the entire crop-growing season is believed to increase soil erosion and damage the mycelium network via the mechanical breakdown of macro-aggregates [13]. Therefore, CT combined with the improper management of straw are some of the leading practices that reduce SOC storage and threaten sustainable crop production [14].

Crop straw retention and incorporation into the soil is an essential management practice to handle residue; it plays a vital role in improving SOC sequestration and soil physicochemical properties [15], increasing crop yields and improving SOC dynamics. However, most of the crop residues are burned to save time and labor, wasting a precious natural resource and causing environmental pollution that affects human health. The burning of large amounts of rice straw not only decreases organic substances but also negatively impacts soil ecosystem. As a consequence, straw incorporation under RT can positivity alter soil organic carbon, nitrogen (N) dynamics, fertility, crop productivity sustainability, and, consequently, considerably reduce greenhouse gas (GHG) emissions. Many studies stated that soil tillage and straw incorporation affect SOC dynamics, soil quality, fertility, water use efficiency, and crop production in the RWR system. However, since the early 2000s, local farmers have used straw incorporation to enhance soil fertility. Straw incorporation is an often overlooked, yet it is an important factor in the crop management system, because the use of surplus amounts of incorporated straw is unfeasible, as it does not easily mineralize or decompose. Therefore, the impact of residue incorporation with different tillage practices on soil properties and yield attributes in cereal production and grasslands is well documented. However, information on the modes and percent of straw incorporation for a particular crop is still lacking. Generally, at least 30% of the soil surface should be covered with straw, but this is not being accurately implemented for all field conditions. Thus, the aim of this study was to investigate the impact of straw incorporation and tillage methods on crop productivity, total nitrogen (TN), soil organic matter (SOM) content, and SOC storage over two years, from 2016 to 2017, in a rice-wheat cropping system for long-term agricultural sustainability.

2. Materials and Methods

2.1. Experimental Site

A field study was conducted during two rice-growing seasons, 2016 and 2017, at Jiangpu Agricultural Experimental Farm, Nanjing Agricultural University, Pukou district, Jiangsu Province, China. The site is located at 32°0′39.21′′ N and 118°36′46.43′′ E, about 26 m above sea level (Figure 1). The soil in the region is a waterloggogenic paddy soil and belongs to Typic Hapludoll, according to Food and Agriculture Organization (FAO, Rome, Italy) classification [16]. The soil is 36.77% silt (0.002–0.02 mm), 24.61% sand (0.02–2.002 mm), and 38.62% clay (<0.002 mm), classified as clay loam according to the United States Department of Agriculture (USDA, Washington, DC, USA) textural classification [17]. Soil pH was 7.2, total nitrogen (TN) was 0.86 g/kg, available phosphorus (AP) was 32.65 mg/kg, available potassium (AK) was 74.45 mg/kg, organic carbon (OC) was 11.43 g/kg, porosity was 38.30%, soil dry bulk density (ρ_b) was 1.34 g/cm^3, and water content was 26.73%. The experimental site had been under a rice-wheat cropping system for several decades.

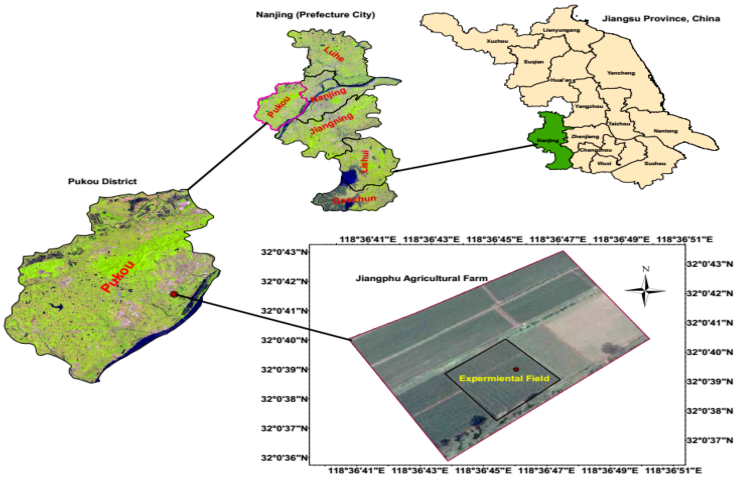

Figure 1. Geographical location of the experimental field site.

2.2. Climate

The area is categorized as sub-tropical monsoon with an average annual rainfall of about 1033 mm; more than 70% of the average annual rainfall occurs between May and September. The average temperature is 15.9 °C, and average sunshine time is 1926 h with a frost-free period of 220 days. The monthly distribution of the maximum and minimum temperatures and rainfall during 2016 and 2017 at the experimental site are depicted in Figure 2.

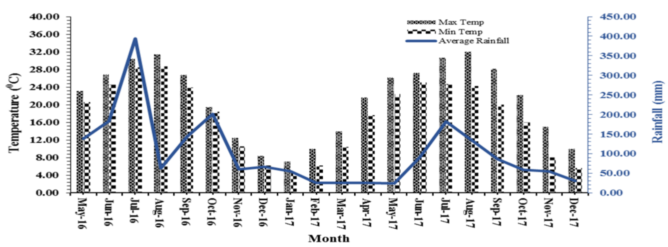

Figure 2. Distribution of mean monthly temperature and rainfall during 2016 and 2017 at the experimental site.

2.3. Experimental Design

The experiment was initiated in June 2016 in a randomized complete block design (RCBD) with four replications. The site was divided into two blocks, and each block was further divided into four plots (32 m^2) separated by a 0.6 m path. The study included eight treatments, including two tillage methods, reduced tillage (RT) and conventional tillage (CT), and four different percentages or modes of straw incorporation: (1) reduced tillage and no straw (RTns), (2) reduced tillage and 30% straw incorporation ($RTsi_{30}$), (3) reduced tillage and 60% straw incorporation ($RTsi_{60}$), (4) reduced tillage and 100% ($RTsi_{100}$), (5) conventional tillage and no straw (CTns), (6) conventional tillage and 30% straw incorporation ($CTsi_{30}$), (7) conventional tillage ad 60% ($CTsi_{60}$), and (8) conventional tillage and 100% ($CTsi_{100}$). Reduced tillage was performed using a rotavator at a depth of 10 cm, whereas conventional tillage was performed using moldboard plowing at a depth of 20 cm followed by two passes with the rotavator. Wheat straw (20.52% lignin, 17.63% hemicellulose, and 34.24% cellulose) was collected from the preceding crop and was chopped into 7–10 cm-long segments [18] and then distributed uniformly on the plots subjected to straw incorporation. Straw was removed using a cutter bar mower from the plots specified for no straw incorporation. A detailed description for these treatments are provided in Table 1.

Table 1. Detailed description of straw incorporation treatments regimens.

Treatments	Description	Symbol
T_1	Reduced tillage (RT), no straw incorporation, and rice crop	RTns
T_2	RT and 30% wheat straw incorporation and rice crop	$RTsi_{30}$
T_3	RT and 60% wheat straw incorporation and rice crop	$RTsi_{60}$
T_4	RT and 100% wheat straw incorporation and rice crop	$RTsi_{100}$
T_5	Conventional tillage (CT), no wheat straw incorporation, and rice crop	CTns
T_6	CT and 30% wheat straw incorporation and rice crop	$CTsi_{30}$
T_7	CT and 60% wheat straw incorporation and rice crop	$CTsi_{60}$
T_8	CT and 100% wheat straw incorporation and rice crop	$CTsi_{100}$

2.4. Soil Sampling and Analysis

After harvesting, a composite soil sample was taken at depths of 0–10, 11–20, and 21–30 cm from five randomly selected locations in each replication with the help of a hand auger. Samples were packed and sealed in polyethylene bags and then shipped to a laboratory to analyze the soil physicochemical properties. The stones, plants, and organic debris were removed with forceps. Soil pH, OC, TN, AP, and AK were measured according to previously reported methods [19]. The soil ρ_b was determined using the core method, and soil porosity was computed from the relationship between particle density (ρ_d) and ρ_b using Equation (1). SOM was obtained by multiplying SOC by a factor of 1.724. The soil carbon storage (SCS) in soil horizons at thicknesses between 0 and 30 cm was calculated using Equation (2) [20].

$$Porosity\ (\%) = (1 - \frac{\rho_b}{\rho_d}) \times 100, \quad (1)$$

in which ρ_b is soil dry bulk density (g/cm^3) and ρ_d is particle density (g/cm^3).

$$SCS = T \times \rho_b \times SOC \times 10000, \quad (2)$$

in which ρ_b is the mean soil dry bulk density at depth of 30 cm, 10,000 is the conversion coefficient, T is the thickness of soil layer (m), and the SCS unit is kg/ha.

2.5. Crop Traits and Yield Measurement

The rice crop was harvested in December for each growing year. To measure yield, threshing was performed manually; then, the product was weighed in kg and converted into yield per hectare.

The crop growth parameters, including thousand-grain weight (TGW), panicle number, and spikes/m^2, were determined at the different crop cycle stages for all treatments during the study period.

2.6. Statistical Analysis

To test the significance and interactions of tillage and different modes of straw incorporation on crop yield, growth parameters, and soil physicochemical properties, analysis of variance (ANOVA) was used, whereas the means were compared using Duncan's multiple range test (DMRT), with $p < 0.05$ level being considered significant. All statistical analyses were conducted using IBM Statistical Package for Social Scientists (SPSS 23.0), and preparation of graphs was completed using Origin Pro 9.

3. Results

3.1. Dry Bulk Density and Total Porosity

The effects of different straw incorporation modes and tillage methods on soil dry bulk density and total porosity at depths of 0–30 cm are presented in Table 2. After two years, soil ρ_b significantly decreased (p < 0.05) under all treatments. The maximum reduction in ρ_b of 9.79% was found under CTsi$_{100}$ followed by RTsi$_{100}$ (6.27%), whereas the smallest reduction (1.31%) occurred under the CTns treatment. The soil dry density marginally increased (0.43%) in RTns compared with the mean value before the experiment. In addition, the depth-wise changes in average soil ρ_b significantly decreased, with the greatest reduction at a depth of 0–10 cm under CTsi$_{100}$ (1.185 g/cm^3) and the least at 20–30 cm in RTns (1.322 g/cm^3). The differences between RTsi$_{30}$ (1.292 g/cm^3) and CTns (1.299 g/cm^3) were non-significant. Moreover, the mean porosity (Table 2) significantly increased in the range of 1.32% to 8.84%, whereas RTns was associated with a non-significant improvement and slight decrease (0.37%) compared to before the experiment. The highest and lowest average porosities were 54.76 and 50.13% in CTsi$_{100}$ and RTns, respectively. Moreover, considerable positive variation in porosity was found at a soil profile depth of 10–20 cm under CTsi$_{100}$, CTsi$_{60}$, RTsi$_{100}$, CTsi$_{30}$, and RTsi$_{60}$, at 54.67, 54.08, 53.56, 53.08, and 52.96%, respectively. Although the homogeneity variance test for mean total porosity in the soil profile (0–30 cm) indicated that differences between RTsi$_{30}$ and CTns were non-significant.

Table 2. Soil dry bulk density (ρ_b) and total porosity at depth (0–30 cm) under different straw incorporation regimes at the end of study.

Soil Physical Parameter	Treatment	Soil Depth (cm)			
		0–10	10–20	20–30	Average
Dry Bulk Density (g/cm^3)	RTns	1.304 ^{a}	1.324 ^{a}	1.337 ^{a}	1.321 ^{a}
	RTsi$_{30}$	1.278 ^{b}	1.295 ^{b}	1.304 ^{b}	1.292 ^{b}
	RTsi$_{60}$	1.249 ^{c}	1.247 ^{c}	1.250 ^{d}	1.249 ^{d}
	RTsi$_{100}$	1.225 ^{d}	1.231 ^{de}	1.259 ^{d}	1.238 ^{e}
	CTns	1.292 ^{ab}	1.299 ^{b}	1.306 ^{b}	1.299 ^{b}
	CTsi$_{30}$	1.255 ^{c}	1.243 ^{cd}	1.279 ^{c}	1.259 ^{c}
	CTsi$_{60}$	1.203 ^{e}	1.217 ^{e}	1.229 ^{e}	1.216 ^{f}
	CTsi$_{100}$	1.185 ^{e}	1.201 ^{f}	1.210 ^{f}	1.199 ^{g}
Total Soil Porosity (%)	RTns	50.79 ^{e}	50.04 ^{f}	49.55 ^{f}	50.13 ^{g}
	RTsi$_{30}$	50.76 ^{d}	51.14 ^{e}	50.79 ^{e}	51.23 ^{f}
	RTsi$_{60}$	52.86 ^{c}	52.96 ^{d}	52.84 ^{c}	52.89 ^{d}
	RTsi$_{100}$	53.76 ^{b}	53.56 ^{bc}	52.48 ^{c}	53.26 ^{c}
	CTns	51.26 ^{de}	50.97 ^{e}	50.71 ^{e}	50.98 ^{f}
	CTsi$_{30}$	52.65 ^{c}	53.08 ^{cd}	51.73 ^{d}	52.49 ^{e}
	CTsi$_{60}$	54.60 ^{a}	54.08 ^{b}	53.63 ^{b}	54.10 ^{b}
	CTsi$_{100}$	55.27 ^{a}	54.67 ^{a}	54.34 ^{a}	54.76 ^{a}

Note: RTns: Reduced tillage (RT) with no straw incorporation, RTsi$_{30}$: RT with straw incorporation (SI) at 30%, RTsi$_{60}$: RT with SI at 30%, RTsi$_{100}$: RT with SI at 100%, CTns: conventional tillage (CT) with no straw incorporation, CTsi$_{30}$: CT with SI at 30%, CTsi$_{60}$: CT with SI at 60%, and CTsi$_{100}$: CT with SI at 100%. Different lowercase letters indicate significant differences at $p < 0.05$. Different letters denote significant differences between treatments at $p < 0.05$.

3.2. Soil Organic Matter (SOM) and Total Nitrogen (TN) in Different Straw Incorporation Treatment

The values in Figure 3 presenting the results for the mean impact of crop straw incorporation on the main soil quality variables, SOM and TN concentration, at various simple depths (0–30 cm). The average SOM content in 2016–2017 significantly increased ($p < 0.05$) by 3.08% to 17.07% under all residue-incorporated treatments. Plots without straw incorporation showed a decreased SOM content (1.69–3.97%) compared with pre-treatment values under reduced and conventional tillage methods. However, the SOM content was higher (25.12, 24.06, 23.83, 23.80, 22.41, and 22.12 g/kg) in the $RTsi_{60}$, $RTsi_{100}$, $CTsi_{100}$, $CTsi_{60}$, RTsi30, and $CTsi_{30}$ treatments, respectively, compared to RTns (21.10 g/kg) and CTns (20.61 g/kg). The SOM difference between $CTsi_{60}$ and $CTsi_{100}$ was non- significant in the 0–30 cm soil profile depth. Moreover, SOM in the topsoil (0–10 cm) was higher in $RTsi_{60}$ (26.31 g/kg) and $CTsi_{60}$ (24.51 g/kg) under RT and CT, respectively.

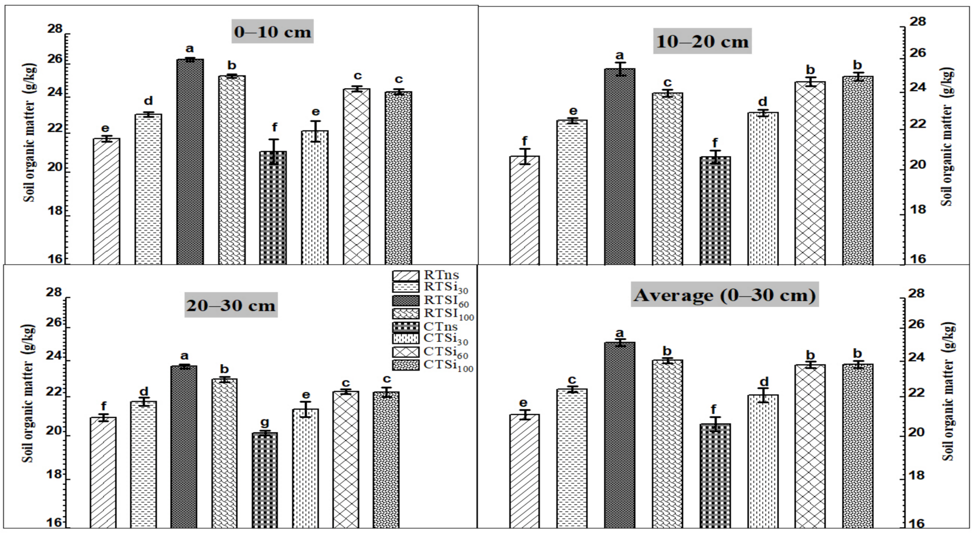

Figure 3. Depth-wise distribution of mean soil organic matter (SOM) under each treatment. Note: RTns: RT without straw incorporation, $RTsi_{30}$: RT with straw incorporation (SI) at 30%, $RTsi_{60}$: RT with SI at 60%, $RTsi_{100}$: RT with SI at 100%, CTns: CT without straw incorporation, $CTsi_{30}$: CT with SI at 30%, $CTsi_{60}$: CT with SI at 60%, and $CTsi_{100}$: CT with SI at 100%. Different letters denote significant differences between treatments at $p < 0.05$, and error bars indicate the standard deviation (SD) of the mean value from 2016 to 2017.

Furthermore, the soil TN concentrations were significantly variable ($p \leq 0.05$) among different straw incorporation management options and tillage practices (Figure 4). Consequently, TN content in all experimental treatments demonstrated an increasing trend, except for CTns. The average TN content increased in the range of 1.17 to 14.51% in the soil profile (0–30 cm) compared with the pre-analyzed value. The mean maximum TN (0.981 g/kg) was found with RTsi60, and the lowest (0.848 g/kg) was found under CTns after two rice crop growing cycles. Moreover, a considerable positive variation in TN was recorded at 10–20 cm in RTsi60 (1.051 g/kg), which was higher than CTsi60 (0.926 g/kg) treatments under RT and CT methods.

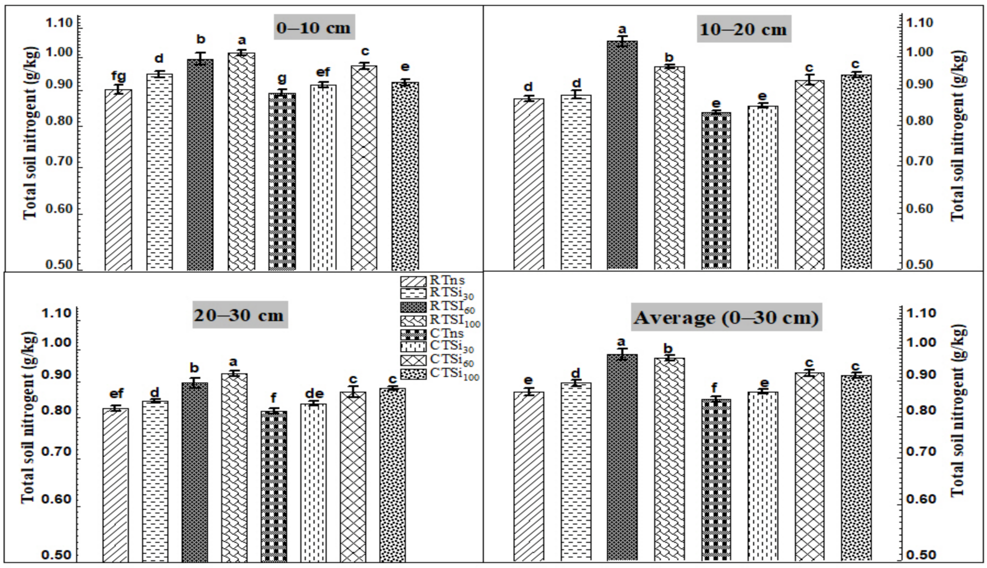

Figure 4. Changes Mean total soil nitrogen at different soil depths under all experimental treatments in 2016 and 2017. Different letters indicate significant differences between treatments at $p < 0.05$ and error bars denote means ± SD (n = 3).

3.3. Soil Carbon Storage (SCS) under Different Treatments

The effect of residue incorporation under RT and CT methods demonstrated that soil carbon storage (SCS) significantly increased ($p < 0.05$) at the end of two rice seasons from 2016 to 2017 (Table 3) in the soil layer (0–30 cm). Compared with the no straw incorporation treatment level in RTns, the SCS with the RTsi$_{60}$, RTsi$_{100}$, and RTsi$_{30}$ treatments increased by 14.20% ($p < 0.05$), 8.82% ($p < 0.05$), and 4.60% ($p < 0.05$), respectively, under RT tillage methods. In the case of CT practice treatments, the SCS under CTsi$_{60}$, CTsi$_{100}$, and CTsi$_{30}$ were 9.81% ($p < 0.05$), 8.99% ($p \leq 0.05$), and 4.51% ($p < 0.05$), respectively, compared with the CTns treatment associated to no residue incorporation. Moreover, the highest SCS rate was observed under RTsi$_{60}$ (6971.54 kg/ha) among other treatments, whereas the homogeneity Duncan test indicated that the difference between CTsi$_{100}$ (6401.16 kg/ha) and RTsi$_{30}$ (6384.93 kg/ha) was non-significant.

Table 3. Average soil organic carbon storage (SCS) under each treatment.

Treatment	Soil Organic Carbon (SCS, kg/ha) Soil Layer (0–30 cm)
RTns	6104.41 ^{f} ± 20.57
RTsi$_{30}$	6384.93 ^{d} ± 21.60
RTsi$_{60}$	6971.54 ^{a} ± 14.23
RTsi$_{100}$	6643.11 ^{b} ± 16.50
CTns	5874.20 ^{g} ± 17.84
CTsi$_{30}$	6139.10 ^{e} ± 18.03
CTsi$_{60}$	6450.48 ^{c} ± 17.44
CTsi$_{100}$	6402.16 ^{d} ± 18.31

Note: The data are presented as the average of two rice cropping seasons: 2016 and 2017. RTns: RT with no straw incorporation, RTsi$_{30}$: RT with straw incorporation (SI) at 30%, RTsi$_{60}$: RT with SI at 30%, RTsi$_{100}$: RT with SI at 100%, CTns: CT with no straw incorporation, CTsi$_{30}$: CT with SI at 30%, CTsi$_{60}$: CT with SI at 60%, and CTsi$_{100}$: CT with SI at 100%. Different lowercase letters indicate significant differences at $p \leq 0.05$. Different lowercase letters in the same line indicate significant differences at $p < 0.05$ and (±) denotes the standard derivation.

3.4. Crop Growth Parameters

The growth parameters in 2016 and 2017 (Table 4) indicate that the highest average effective spike number was found in CTsi$_{60}$ (309.72×10^4/hm^2) and the lowest in CTns (260.23×10^4/hm^2) after two rice crop growing cycles. However, grains per spike had a significant response ($p < 0.05$) to both tillage practices and different rates of straw incorporation compared to without straw. The average spike per number was higher in $RTsi_{60}$ (132.24) followed by $CTsi_{60}$ (132.24), and the lowest value was recorded in CTns (122.14). Moreover, the mean thousand grain weights (TGW) found in the RT treatment plots were 24.58, 24.43, 24.17, and 24.17 g in $RTsi_{30}$, $RTsi_{60}$, $RTsi_{100}$, and RTns, respectively. For the CT practice plots, the TGW were 24.41, 24.34, 24.23, and 23.73 g in $CTsi_{100}$, $CTsi_{30}$, $CTsi_{60}$, and CTns, respectively, during study period from 2016 to 2017. The results further indicated that the crop performance significantly improved each year with crop straw incorporation under both tillage methods.

Table 4. Influence of different percentages of straw incorporation and tillage methods on the performance of rice growth components.

Year	Treatments	Effective Spike Number ($\times 10^4/hm^2$)	Grains Per Spike	Thousand-Grain Weight (g)
2016	RTns	260.25 ^{c} ± 5.32	119.48 ^{f} ± 1.21	23.96 ^{b} ± 0.24
	$RTsi_{30}$	276.25 ^{b} ± 5.23	124.21 ^{d} ± 0.85	24.52 ^{a} ± 0.21
	$RTsi_{60}$	293.25 ^{a} ± 3.00	133.23 ^{a} ± 0.47	24.33 ^{a} ± 0.20
	$RTsi_{100}$	278.12 ^{b} ± 7.00	122.10 ^{e} ± 0.45	24.43 ^{a} ± 0.37
	CTns	249.25 ^{d} ± 1.04	122.17 ^{e} ± 0.28	23.58 ^{c} ± 0.17
	$CTsi_{30}$	257.25 ^{cd} ± 2.76	126.10 ^{c} ± 0.28	24.20 ^{ab} ± 0.10
	$CTsi_{60}$	301.23 ^{a} ± 5.50	128.00 ^{b} ± 0.53	23.88 ^{bc} ± 0.10
	$CTsi_{100}$	283.12 ^{b} ± 4.19	120.10 ^{f} ± 0.25	24.36 ^{a} ± 0.16
2017	RTns	267.25 ^{c} ± 7.13	117.00 ^{g} ± 0.78	24.32 ^{a} ± 0.20
	$RTsi_{30}$	288.35 ^{b} ± 3.61	125.52 ^{c} ± 0.18	24.63 ^{a} ± 0.12
	$RTsi_{60}$	325.25 ^{a} ± 7.05	131.24 ^{a} ± 0.78	24.52 ^{a} ± 0.31
	$RTsi_{100}$	290.12 ^{b} ± 6.16	125.61 ^{c} ± 0.13	23.90 ^{b} ± 0.08
	CTns	271.20 ^{c} ± 1.03	122.10 ^{f} ± 0.94	23.88 ^{b} ± 0.12
	$CTsi_{30}$	292.22 ^{b} ± 2.10	123.32 ^{e} ± 0.23	24.48 ^{a} ± 0.15
	$CTsi_{60}$	318.20 ^{a} ± 2.02	128.10 ^{b} ± 0.61	24.57 ^{a} ± 0.12
	$CTsi_{100}$	294.17 ^{b} ± 6.10	124.42 ^{d} ± 0.69	24.46 ^{a} ± 0.21
Average	RTns	263.75 ^{e} ± 6.23	118.24 ^{f} ± 1.00	24.14 ^{c} ± 0.22
	$RTsi_{30}$	82.30 ^{c} ± 4.42	124.87 ^{c} ± 0.52	24.58 ^{a} ± 0.16
	$RTsi_{60}$	309.25 ^{a} ± 5.02	132.24 ^{a} ± 0.62	24.43 ^{ab} ± 0.26
	$RTsi_{100}$	284.12 ^{bc} ± 6.58	123.86 ^{d} ± 0.29	24.17 ^{c} ± 0.22
	CTns	260.23 ^{e} ± 1.03	122.14 ^{e} ± 0.61	23.73 ^{d} ± 0.14
	$CTsi_{30}$	274.74 ^{d} ± 2.43	124.71 ^{c} ± 0.25	24.34 ^{bc} ± 0.13
	$CTsi_{60}$	309.72 ^{a} ± 3.76	128.05 ^{b} ± 0.57	24.23 ^{bc} ± 0.11
	$CTsi_{100}$	288.65 ^{b} ± 5.14	122.26 ^{e} ± 0.47	24.41 ^{ab} ± 0.18

Note: Different lower case letters in the same line indicate significant differences at $p < 0.05$ and (±) denoted by Standard Derivation.

3.5. Crop Yield with Different Modes of Straw Incorporation under Both Tillage Methods

Crop yield was different between 2016 and 2017 under the different treatments (Figure 5). This difference was not necessarily related to the soil management practices, but perhaps to the climate. Straw incorporation had a significant impact ($p \leq 0.05$) on annual rice production compared to the without straw incorporation treatments. The mean rice grain yield of the eight treatments in 2016 and 2017 were 7316.98 and 7977.48 kg/ha, respectively. The highest average yield was recorded in $RTsi_{60}$ with reduced tillage (8274 kg/ha), and the lowest was found in CTns at 7172 kg/ha. The highest mean paddy yield with RT was $RTsi_{60}$, 15.02% higher than the RTns treatment. For the CT practice group, the $CTsi_{60}$ produced a 10.95% higher yield compared to the CTns treatment. However, more significant differences existed between treatments in 2017 than in 2016. In 2017, the yield production of the various treatments ranged from 7539 to 8623 kg/ha. However, comparison of the straw incorporation with the no straw incorporation treatments showed that the average crop yield was ranked as follows: $RTsi_{60} > CTsi_{60} > RTsi_{30} > CTsi_{30} > RTsi_{100} > CTsi_{100} >$ RTns > CTns under both treatments. Furthermore, these results indicate that the reduced tillage method with straw incorporation was more conducive to increasing rice production.

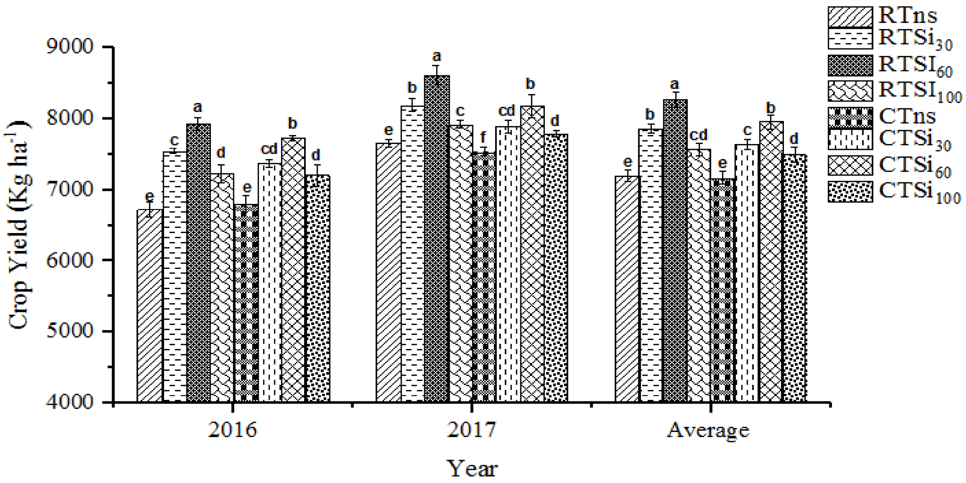

Figure 5. Influence of straw incorporation and tillage practices on rice crop yields under each treatment. Note: Bars denote the standard derivation, and different lowercase letters indicate significant and homogeneity differences ($p \leq 0.05$) among treatments according to Duncan's test.

4. Discussion

Proper field management practices, such as tillage methods and straw management practices [21], can improve soil quality, playing an essential role in crop growth and production. The results of this study indicated that straw incorporation has positive effects on soil physicochemical characteristics, soil organic matter concentration, and yields in RWR systems compared to systems that do not incorporate straw with RT and CT practices.

Tillage and straw incorporation significantly affected soil ρ_b at depths of 0–30 cm under all treatments (Table 2). By the end of the two-year experiment, mean soil dry bulk density decreased by 8.37% for $CTsi_{100}$ and 6.73% for $RTsi_{100}$ compared to the CT and RT treatments without straw incorporation, respectively. Our study demonstrated that 100% straw incorporation in both RT and CT treatments may have relatively positive effects on soil ρ_b, decreasing as soil depth increased. This might be due to the incorporation of the aboveground crop residue into the soil layer. Prior studies also demonstrated that residue incorporation into soil effectively improved the soil structure and helped reduce soil dry bulk density compared to the treatments without straw [21–23]. In terms of the soil profile layer (0–30 cm) and residue incorporation, we showed that soil dry bulk density significantly decreased the most in the topsoil layer, from depths of 0 to 10 cm, in all treatments. These findings are closely linked to those of Mi et al. [24], who reported that straw incorporation beneficially affected the reduction of soil ρ_b by 8–11% in the topsoil layer under both RT and CT in rice cropping.

Straw incorporation and tillage methods significantly increased ($p < 0.05$) soil total porosity (0–30 cm) in both 2016 and 2017. The increase in soil porosity might be due to the addition of crop straw, which helped loessal soil particles to form aggregates. This is consistent with the findings of Mulumba et al. [25], who stated that long-term residue incorporation has increasingly positive impacts on soil porosity. Previous studies also found that soil porosity increased by 5.5% at soil depths of 0–30 cm, with straw incorporation practices compared with traditional methods [26,27]. Additionally, Zhang et al. [28] reported that straw incorporation increased the SOC concentration and reduced bulk density, thereby improving total porosity, aeration, and water-holding capacity.

Extensive research studies have proven that long-term crop straw incorporation can result in a substantial increase in organic C in the soil and may reduce or offset the SOM losses caused by conventional, continuous tillage and intensive cropping [29,30]. Minimal tillage or RT generally increased the SOM of the plow layer [31] under rice-wheat cropping (RWC) system, because RT can reduce soil disturbance and promote root growth in the topsoil, thus enhancing soil aggregate stability [14] and increasing SOM in the soil profile. Kabiri et al. [32] and Muhammad et al. [33] reported that water-logged conditions in paddy fields generate anaerobic environment and reduce the rate of SOM mineralization by limiting the microbial population and their growth; also, Zhou et al. [34] demonstrated that wheat straw incorporation is the best approach to maximize C accumulation and reduce atmospheric carbon, which improves the physical conditions of the soil and subsequently enhances the root development for crop production. Other studies [24,35] reported that paddy soils play a crucial role in total carbon sequestration and a sink for global C. The results in our study demonstrated that wheat residue incorporation significantly increased the SOM level by 3.08–17.07% compared to the treatments without straw at depths of 0–30 cm after two rice growing seasons (Figure 3). This trend was most likely associated with the amount of crop straw incorporated in the treatments, as suggested by other studies [36,37]. The highest mean SOM content was found with $RTsi_{60}$. This increase in SOM content might be due to the higher percentage of straw incorporated into the soil with the least soil disturbance using the RT method, which improved the quality of soil in terms of chemical properties [38,39]. Another study conducted by Xu et al. [40] indicated that significant differences in SOC concentration (0–40 cm) were observed with tillage and straw retention practices in China over the four-year experiment. In our study, the interannual differences in SOM increased in a relatively stable trend, likely because the changes in soil organic content were usually insensitive to the current management methods. Changes mainly occurred when smaller quantities of crop residues were incorporated into the soil [41]. Similarly, Yadav et al. [23] and Mi et al. [24] concluded that SOM significantly improved with the incorporation of straw into the soil profile at depths of 0–40 cm under RWR system.

Soil total nitrogen (TN) is one of the main factors for determining soil fertility. Traditional activities, such as cropping methods and field management, play an essential role in the accumulation of N in soil for agricultural sustainability [42]. However, the TN concentration was lower in the CT treatments as compared to RT with straw incorporation during two rice crop seasons in our study. The highest TN content was observed under $RTsi_{60}$ and $RTsi_{100}$ followed by the $CTsi_{60}$ treatment (Figure 4). This might be due to different amounts of incorporated wheat straw, because higher rates of straw incorporation positively affect sustaining TN content when using the RT method. As such, straw incorporation may facilitate the reduction in soil dry bulk density, increase SOM content, and improve soil water retention and aggregation [43]. Therefore, the incorporation of straw is beneficial for the accumulation of N in the soil to enhance soil fertility. Similar results were previously reported by the authors of [44], who found higher TN content under conservation tilling than conventionally tilled soil in continuous spring wheat cropping. Other studies [43,45] also reported that incorporation of higher amounts of residue into the soil improved *N* content, which may be relative to *N* supply from the wheat straw or the enhanced physical and chemical condition of the soil.

Moreover, many factors influence SOC sequestration including crop residue incorporation, retention, cropping rotation, tillage management, and cropping systems. These factors are often directly related to changes in the soil organic carbon storage (SCS) in agricultural soils [46,47]. However, our study of straw incorporation showed that SCS increased with a trend similar to that of SOM under all straw incorporation treatments (Table 3). However, the highest SCS was found with RT with 60% wheat straw incorporation. These findings are closely linked to the study by Zhang et al. [48], who reported that SOC stocks were higher by 25.94% and 26.98% under CT and RT practices, respectively, when incorporating straw over the seven years of the experiment. Conversely, Zhang et al. [22] demonstrated that SOC storage was significantly higher by 29.7% and 17.7% at depths of 0–10 and 10–20 cm, respectively, when incorporating different amounts of residue.

Previous studies by Tripathy et al. [27], Karami et al. [43], and Memon et al. [49] showed that straw incorporation is a key management strategy to enhance crop production, along with improved soil fertility and water availability [50]. Additionally, straw incorporation decreases the un-productive component of evapotranspiration and creates favorable root environment by improving soil structure, which provides a clean, uniform seedbed that facilitates crop establishment [51]. In our study, rice grain yield (Figure 5) and growth parameters (Table 4) were significantly ($p < 0.05$) higher when straw was incoporated into the soil compared to the treatments without straw incorporation. Soil tillage methods, such as RT and CT, had no significant effect ($p > 0.05$) on grain yield in either rice growing season. The highest grain yield, useful spike number, and grains per spike were higher under RTsi$_{60}$, followed by CTSI$_{60}$, whereas TGW was marginally higher under RTsi$_{30}$ for both years. These results reveal that 60% straw incorporation into the soil for either tillage practice had a progressively positive impact on the rice crop grain yield compared to 100% straw or without straw incorporation. This may be due to the excessive amount of incorporated crop straw, which could not be mineralized or appropriately decomposed. Previous studies [52,53] also stated that higher amounts of straw incorporation affected the emergence rate of the rice crop and the growth quality at the seedling stage. These findings are also supported by prior research [23,28,54], which concluded that higher rice grain yields were produced by the balanced input of residue with RT methods compared to the control or other nutrient management practices.

5. Conclusions

Our study has shown that both reduced tillage (RT) and conventional tillage (CT) with 60% wheat straw incorporation reduced soil ρ_b and increased soil porosity, TN, SOM, SCS, and grain yield. The results also indicated that RT with 60% straw incorporation significantly improved soil quality and structure at depths of 0–30 cm. We suggest that the adoption of conservation tillage (RT), along with 60% straw incorporation, may be a promising soil management practice to enhance both rice grain yield and soil quality to improve the agricultural sustainability of rice–wheat rotation fields. Future studies should be completed to investigate the effect of straw incorporation with different soil textures, water contents, and climate conditions.

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