



EFFECTS OF TILLAGE AND STRAW MANAGEMENT ON SOIL PHYSICAL PROPERTIES AND CROP YIELD UNDER SUSTAINABLE AGRICULTURAL PRODUCTION

Markkord W Pasweth¹, J. Marimuthu², Harsh Srivastava³

¹Bio Resources Development Centre, Upper Shilong, Kannur, Kerala, E-mail: markpasweth@gmail.com

²Ph. D Scholar, Department of Vegetable Science, Horticultural College and Research Institute, coimbatore, Tamil Nadu Agricultural University, Tamil Nadu, India, Email ID - jmarimuthu2042000@gmail.com

³Masters in Microbiology, Shoolini University of Biotechnology and Management Science, Himachal Pradesh, India, Email Id: Shrivastavaharsh589@gmail.com

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Abstract

The impact of different tillage and straw-management systems on soil structural properties, nutrient retention, soil quality and crop productivity under sustainable agricultural production was evaluated in this study. Five management systems were taken into consideration: bare soil, conventional tillage, no-till with straw mulching, trench-applied straw mulching and surface straw mulching. Water-stable aggregate distribution, mean weight diameter, geometric mean diameter, percentage aggregate destruction, aggregate-associated SOC and soil N were water applied as indicators of soil response, along with soil quality index. Yields of peanut and rapeseed were also compared by treatments grown. In general, the straw-retaining systems had a better soil structure than that of bare soil and conventional tillage. The no-till system with straw mulching and surface straw mulching gave better aggregate stability and soil quality, and the trench-applied straw mulching improved the carbon and nitrogen contents in some aggregates. The peanut yield was significantly higher under all straw-management treatments than the peanut yield under the non-straw treatment; the peanut yield under surface straw mulching was the highest, while the peanut yield under trench-applied straw mulching was also the highest. The overall results of the reduced soil disturbance coupled with good straw return are positive on soil aggregation, soil nutrient content and crop productivity, which shows the benefit for sustainable and resilient agricultural production. The results highlight the practicality of integrated soil residue management as a soil restoration technique.

Keywords: Tillage; Straw management; Soil aggregation; Soil quality; Crop yield



1. Introduction

Sustainable agricultural production is dependent on management practices that are capable of maintaining adequate soil structure, conserving soil nutrients and sustaining the productivity of the crop in a way that minimises degradation as a consequence of intensive cultivation. Water movement, root development and growth, aeration, nutrient cycling, and crop response to environmental stress are all closely related to soil physical condition. Soil tillage and management of soil residues are thus important part of sustainable soil management as they affect soil disturbance, aggregation, turning over of soil organic matter and water holding capacity. Soil organic matter plays a significant role in soil quality because it is linked to soil fertility and its structural stability and impacts on the productivity of crops (Lal, 2020). Retention of residues in the soil may lead to soil C accumulation and enhance the soil's potential for C storage (Berhane et al., 2020).

While conventional tillage can provide better seedbed preparation and ease soil compaction, may destroy soil aggregates with repeated tillage, and speed up the decomposition of organic matter, it can also decrease long-term structural stability. Conservation tillage has thus been the subject of interest as a soil disturbance reduction strategy for crop production. Conservation tillage practices have been shown to increase soil organic carbon and crop production; however, the response is soil, climate and cropping system dependent (He et al., 2022). No-till minimizes soil disturbance and the loss of surface residues, but it is not always an effective strategy for carbon storage, underscoring the need for additional residue management strategies (Blanco-Canqui, 2021). Additionally, tillage changes water-use efficiency and grain productivity through altering the infiltration, evaporation and rooting environment (Kan et al., 2020).

Straw return is one of the key measures to recycle crop residues and is a way of improving soil fertility. Straw returning to soil provides soil with organic substrates, nutrient cycling, and affects soil aggregation, carbon storage, and crop performance. The effects of the various straw-returning methods will vary because the position of the straw residue affects the conditions for the decomposition, soil contact, and release of nutrients. Appropriate straw returning systems have been reported to improve soil organic carbon, total nitrogen, available nutrients, and yield (Huang et al., 2021). In the same way, higher straw returned rates change the soil physicochemical properties and enhance crop production when straw input is scientifically managed (Che et al., 2024). Buried straw management improves the productivity of crops and changes the soil organic matter transformation by promoting straw incorporation into the cultivated soil (Li et al., 2020).

The tillage-Straw management interaction is important because tillage affects returned straw decomposition, redistribution and stabilization. The results from the meta-analysis suggest that straw return effect on soil carbon is related to tillage system (Islam et al., 2023). Compared with single use of straw-return or tillage, the combined use of the two methods has been proven to be more efficient in promoting soil quality and sustainable crop yields (Li et al., 2022). The same integrated system can enhance soil organic carbon, maize yield and carbon balance of agricultural fields (Zhang et al., 2022). The results of the assessment suggest measurable variations in soil organic carbon storage and crop production with the different straw-management practices (Islam et al., 2024).

The management of sustainable residues is a trade-off between productivity and carbon sequestration and environmental performance. The straw return system is beneficial for yield and carbon storage, but the results are influenced by management intensity, decomposition conditions and crop needs (Liu



et al., 2023). The effects on straw return and management over the years on soil quality are also affected, and the improvement in soil quality is also associated with the improvement of crop performance (Wang et al., 2023). The adoption of reduced tillage, residue retention, and better nutrient management has proven to be beneficial for soil carbon, crop yield, water productivity, and economic sustainability in integrated crop-management systems (Biswakarma et al., 2021). The results can aid in the design of soil structural indicators and crop productivity that are evaluated as a whole and not separately.

This study aims to analyze the effects of different kinds of tillage and straw management on soil physical condition and crop production in sustainable agriculture. A focus is placed on soil aggregate distribution, aggregate stability, soil organic carbon and nitrogen with various aggregate sizes, the overall soil quality, and the production performance of peanut and rape.

Objectives:

1. The objective was to determine the impact of two tillage and two straw-management systems on soil aggregate distribution and aggregate-stability indicators.
2. To determine the change in soil organic carbon, total nitrogen and overall soil quality following treatment in aggregates.
3. To examine the effects of various management practices on peanut and rapeseed production and to correlate the productivity response with the changes in soil condition.

2. Materials and Methods

2.1 Study Design and Data Source

This study was based on secondary analysis of the dataset “An adaptive straw returning strategy proves more effective in improving soil quality and increasing yields of newly reclaimed red croplands.” A long-term field experiment was designed on newly reclaimed red cropland for the purpose of studying the effects of different tillage and straw return contents on soil quality and yield of crops. The dataset was constructed based on a long-term field experiment which was established on newly reclaimed red cropland to evaluate the impacts of different soil tillage and straw return contents on soil quality and crop productivity. The experiment consisted of 15 plots each distributed across five management treatments with 3 plots per treatment. The observations made were for the following peanut–rapeseed rotation cycles from 2018 to 2023. Soil measurements were mostly made in the 0-20 cm soil layer. In the present analysis, soil aggregate distribution, aggregate stability, aggregate-associated soil organic carbon and total nitrogen, soil quality indicators and peanut and rapeseed yields were considered (Ye et al., 2025).

2.2 Tillage and Straw Management Treatments

The following five management treatments were tested: bare soil (BS), conventional tillage (CT), no-till with straw mulching (NM), trench-applied straw mulching (TM), and surface straw mulching (SM). The uncropped cultivation system (BS) was compared with the conventional cultivation system (CT). Three alternative straw-returning methods were used, each associated with different soil disturbance either in its intensity or its type: NM, TM, and SM. The above mentioned treatments were not factorial combinations of the tillage and straw factors, but rather integrated management systems,



and therefore considered a single categorical management variable for the statistical analysis. The relative impact of the straw-management treatments was estimated using the principal cultivated reference of CT.

2.3 Soil Aggregate Distribution and Stability

Soil structural condition was determined by the percentage of water-stable aggregates larger than 2 mm in diameter, 2–1 mm in diameter, 1–0.5 mm in diameter, 0.5–0.25 mm in diameter and less than 0.25 mm in diameter. The percentage contribution of an aggregate fraction was calculated as:

$$W_i = \frac{M_i}{M_t} \times 100$$

where W_i denotes the percentage of aggregate fraction i , M_i is the mass of aggregates within that fraction, and M_t the total mass of soil analyzed. Mean weight diameter (MWD), geometric mean diameter (GMD) and percentage aggregate destruction (PAD) were used to further characterise the aggregate stability. MWD was calculated as:

$$MWD = \sum_{i=1}^n X_i W_i$$

where X_i is the mean diameter of the aggregate class i and W_i is the mass percentage of the aggregate class i . The estimated value of GMD was:

$$GMD = \exp \left(\frac{\sum_{i=1}^n W_i \ln X_i}{\sum_{i=1}^n W_i} \right)$$

The higher the MWD and GMD, the higher the aggregate stability. PAD was calculated as:

$$PAD = \frac{D_a - W_a}{D_a} \times 100$$

where D_a is the proportion of dry sieved macroaggregates, and W_a is proportion of water-stable macroaggregates. Low PAD values meant more resistance of the aggregates to breakdown.

2.4 Aggregate-Associated Carbon and Nitrogen

Soil organic carbon (SOC) and total nitrogen (TN) were examined across the aggregate fractions >2 mm, 2-1 mm, 1-0.5 mm, 0.5-0.25 mm, 0.25-0.053 mm, and <0.053 mm. The distribution of carbon and nitrogen among soil aggregates was compared among treatments to determine if tillage and straw management affected the distribution of these resources. The C/N ratio was determined to be:

$$C:N = \frac{SOC}{TN}$$



soil organic carbon concentration (SOC) and total nitrogen concentration (TN) in the respective aggregate fraction. The relationship between soil structural development and nutrient retention was assessed by determining the distribution of SOC and TN by aggregate class.

2.5 Soil Quality Assessment

The overall soil condition was evaluated based on the soil quality index (SQI) available, along with MWD, GMD, PAD, soil texture and physicochemical indicators. The data comprised SOC, TN, TP, NH₄-N, NO₃-N, AP, AK, pH, sand, silt, clay, aggregate stability parameters and SQI. But, conceptually, the SQI can be expressed as:

$$SQI = \sum_{i=1}^n W_i S_i$$

where W_i is the weighting coefficient assigned to soil indicator i , S_i is the soil indicator's standardized score, and n is the number of soil indicators included. The higher the SQI the better the overall soil quality was considered.

2.6 Crop Yield Assessment

Peanut and rapeseed yields were recorded in the data and used to assess productivity. Peanut yield data was for 2018-2022 while the rapeseed yield data was for 2019-2023. The comparisons were made of yield among the three different tillage systems, CT, NM, TM, and SM since BS represented bare soil and was not used for making any crop-yield observations. Mean yield for each treatment was determined as:

$$\bar{Y} = \frac{\sum_{i=1}^n Y_i}{n}$$

where $\bar{Y}$ is the mean yield, Y_i is the yield recorded in year i , and n the number of years of observations. This was calculated as relative yield improvement as compared to conventional tillage:

$$RYI = \frac{Y_t - Y_{CT}}{Y_{CT}} \times 100$$

where Y_t is the yield under NM, TM, or SM, and Y_{CT} is the corresponding yield under conventional tillage.

2.7 Statistical Analysis

Soil and crop responses were summarized using descriptive statistics such as mean, standard deviation, absolute differences and percentage changes. The five treatments were integrated management systems, which were not factorial combinations, and management treatment was therefore analyzed as a single categorical treatment. If replicate-level data is available, variations between treatments were assessed by one-way analysis of variance (ANOVA):

$$Y_{ij} = \mu + T_i + \epsilon_{ij}$$



where Y_{ij} is the observed response, μ is the overall mean, T_i is the fixed effect of management treatment, and ε_{ij} is the residual error. Where significant treatment effects were detected, Tukey's honestly significant difference test was applied to make pairwise comparisons when significant treatment effects were found. A level of $p < 0.05$ was considered statistically significant. Correlation analysis was used to determine associations among the soil physicochemical properties, aggregate stability indicators and SQI. The peanut and rapeseed yields were analysed separately due to the different crop seasons and calendar years.

2.8 Integrated Assessment of Soil and Crop Responses

The overall effectiveness of the treatments was assessed in relation to soil aggregation, nutrient retention, soil quality and crop productivity. The changes in macroaggregate distribution, MWD, GMD, PAD, aggregate-associated SOC and TN, SQI, and crop yield were evaluated to see if management practices that promoted better soil structural condition also yielded improved soil productivity. The integrated assessment was used as a standard for the assessment of the contribution of tillage and straw-management strategies to sustainable agricultural production.

2.9 Ethical Considerations

No human subjects, personal data, or experimental animals were involved in this study as it was a secondary analysis of an existing agricultural field-experiment data set. So formal (human or animal) ethical approval was not relevant. Experimental values were not fabricated or altered, but only used as they were available in the original data set. Data were analysed uniformly across treatments and the original data source was cited to ensure transparency, responsibility, and reproduction of publicly available research data.

3. Results

3.1 Effect of Tillage and Straw Management on Soil Aggregate Distribution

Water-stable aggregates showed significant differences between the five management treatments. Table 1 shows that the smallest proportion of aggregates larger than 2 mm was found on bare soil with a mean of 3.48%, while the proportions on NM and SM were fairly high, at 15.11% and 14.35% respectively. An intermediate value was obtained with the conventional tillage of 8.82%. The percentage of the smallest aggregate fraction (< 0.25 mm) was the reverse case. Bare soil contained 56.40% of aggregates in this fraction, compared with 47.57% under CT, 44.73% under TM, 37.33% under NM, and 37.06% under SM.

From this, it can be inferred that the size of aggregates was increased to the structural units under straw-retaining treatments, especially the NM and SM. The aggregate-size distributions for the five management systems are shown in Figure 1.

Table 1. Distribution of water-stable soil aggregates under different management treatments



Treatment	>2 mm (%)	2–1 mm (%)	1–0.5 mm (%)	0.5–0.25 mm (%)	<0.25 mm (%)
BS	3.48 ± 0.73	7.90 ± 3.01	13.87 ± 0.25	18.35 ± 0.48	56.40 ± 3.97
CT	8.82 ± 1.31	9.87 ± 0.52	15.75 ± 2.56	17.98 ± 3.68	47.57 ± 5.46
NM	15.11 ± 2.82	11.06 ± 2.14	16.73 ± 0.87	19.76 ± 0.26	37.33 ± 3.83
TM	8.07 ± 0.88	9.93 ± 0.60	18.70 ± 0.26	18.57 ± 1.38	44.73 ± 1.91
SM	14.35 ± 5.61	9.80 ± 1.24	18.32 ± 0.94	20.47 ± 0.02	37.06 ± 7.81

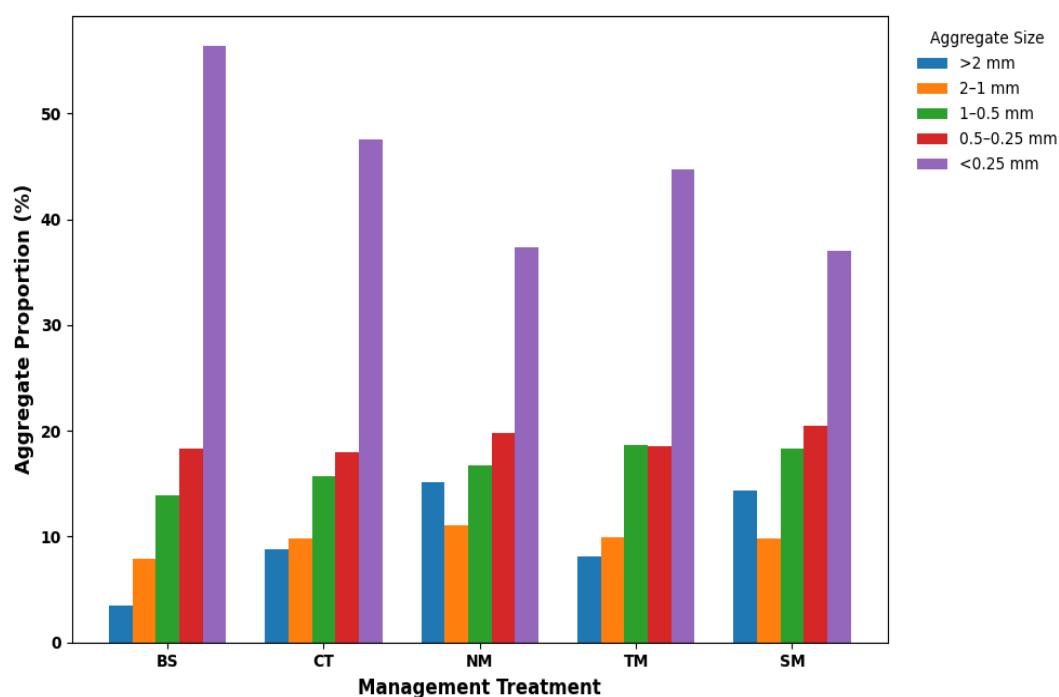


Figure 1. Distribution of water-stable aggregate size fractions under bare soil, conventional tillage, no-tillage straw mulching, trench straw mulching, and surface straw mulching treatments

3.2 Changes in Soil Aggregate Stability and Soil Quality

Significant differences were observed between treatments in aggregate-stability indices. As can be seen in Table 2, MWD rose from 0.431 under BS to 0.569 under CT and peaked at 0.714 under NM.



The MWD for the sample of SM was also relatively high, at 0.695. The relative MWD to CT was about 25.45% and 21.96% higher for NM and SM, respectively.

The same trend was found in the case of GMD. Under CT, the best result, NM had 0.4222 with SM at 0.4214. PAD showed the reverse response, decreasing from 0.5434 under BS to 0.4489 under CT, 0.4163 under TM, 0.3386 under NM, and 0.3324 under SM. Under NM, the reductions in PAD relative to CT were about 24.56% while under SM, the reductions were 25.94%.

Management had a significant effect on soil quality index as well. The SQI of CT, NM and SM were 0.412, 0.638 and 0.632 respectively, as compared to 0.231 for BS. In terms of comparison, SQI was about 54.99% higher when compared to CT under NM and 53.37% higher when compared to CT under SM. The responses of the MWD, GMD and PAD are compared in Figure 2 and the difference between the treatments in SQI is depicted in Figure 3.

Table 2. Soil aggregate stability and soil quality indices under different management treatments

Treatment	MWD	GMD	PAD	SQI
BS	0.431 ± 0.055	0.264 ± 0.025	0.543 ± 0.039	0.231 ± 0.011
CT	0.569 ± 0.008	0.330 ± 0.021	0.449 ± 0.057	0.412 ± 0.041
NM	0.714 ± 0.076	0.422 ± 0.048	0.339 ± 0.038	0.638 ± 0.020
TM	0.576 ± 0.013	0.343 ± 0.010	0.416 ± 0.017	0.551 ± 0.017
SM	0.695 ± 0.128	0.421 ± 0.085	0.332 ± 0.084	0.632 ± 0.054

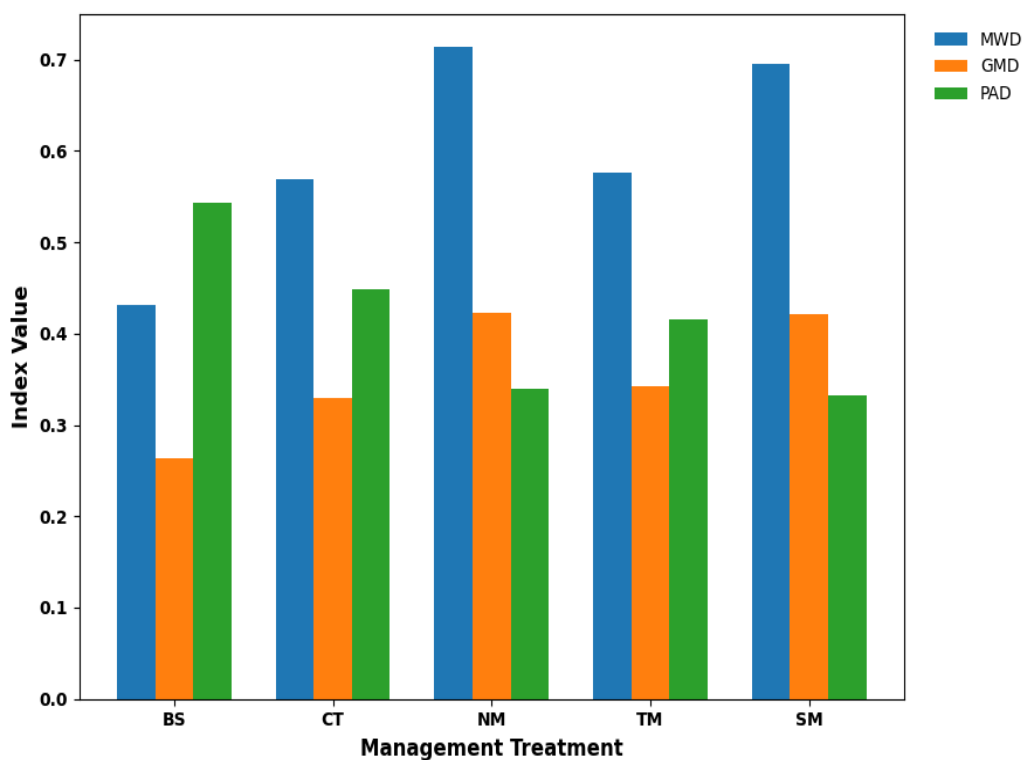


Figure 2. Variation in mean weight diameter, geometric mean diameter, and percentage aggregate destruction across the five soil-management treatments

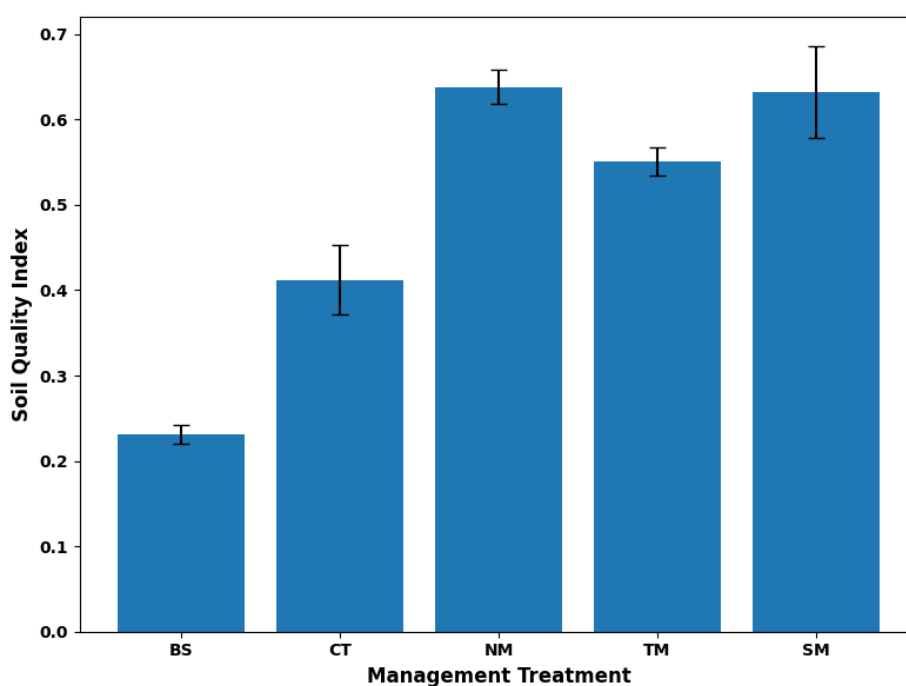




Figure 3. Soil quality index under different tillage and straw-management treatments

3.3 Aggregate-Associated Soil Organic Carbon

Soil organic carbon was found to be different for both managements and aggregate-size classes. The results of the SOC presented in Table 3, showed that TM had the highest SOC concentration in the >2 mm fraction with 6.94, while the CT and BS had 5.63 and 5.76 respectively. The SOC concentration was also the greatest for the fraction 0.5–0.25 mm in TM, at 6.62.

The SOC values for SM were relatively high in the intermediate aggregate fractions: 5.57 in 1–0.5 mm and 5.23 in 0.25–0.053 mm. NM had 5.61 in the 0.5-0.25 mm fraction, which was also higher than CT (5.17). Across all aggregate size classes, straw-returning treatments generally resulted in higher SOC concentrations than conventional tillage.

Table 3. Soil organic carbon across aggregate size fractions under different treatments

Treatment	>2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	0.25–0.053 mm	<0.053 mm
BS	5.76 ± 0.43	4.92 ± 1.12	4.19 ± 1.12	4.00 ± 1.22	3.66 ± 1.07	4.03 ± 0.83
CT	5.63 ± 1.48	4.54 ± 0.97	4.37 ± 0.23	5.17 ± 0.64	4.65 ± 0.66	4.00 ± 0.23
NM	5.15 ± 0.48	4.54 ± 0.63	5.06 ± 0.11	5.61 ± 0.74	4.58 ± 0.55	4.55 ± 0.43
TM	6.94 ± 2.30	4.59 ± 0.80	4.32 ± 0.34	6.62 ± 2.05	5.43 ± 0.54	4.85 ± 0.06
SM	5.98 ± 1.23	4.82 ± 0.18	5.57 ± 0.02	5.60 ± 0.23	5.23 ± 0.34	4.68 ± 0.28

3.4 Aggregate-Associated Total Nitrogen

Variation was also seen with treatment for aggregate-associated TN. The higher concentration of TN in the >2 mm fraction for TM (1.018) was followed by NM (0.873) and SM (0.844) as compared to CT (0.815) and BS (0.680) as shown in Table 4. TN was also relatively high in the other fractions of the aggregate, such as 0.728 in the 2–1 mm fraction and 0.625 in the <0.053 mm fraction.

In most of the aggregate classes, the average TN concentration for both NM and SM was found to be higher than the average for CT. This was particularly true in the fine sized fractions where the straw retaining treatments had higher nitrogen concentrations than the bare soil.



Table 4. Total nitrogen across aggregate size fractions under different management treatments

Treatment	>2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	0.25–0.053 mm	<0.053 mm
BS	0.680 ± 0.048	0.524 ± 0.000	0.466 ± 0.000	0.466 ± 0.000	0.422 ± 0.012	0.408 ± 0.000
CT	0.815 ± 0.000	0.669 ± 0.023	0.582 ± 0.000	0.539 ± 0.012	0.524 ± 0.000	0.509 ± 0.012
NM	0.873 ± 0.048	0.698 ± 0.047	0.640 ± 0.000	0.553 ± 0.024	0.538 ± 0.012	0.596 ± 0.036
TM	1.018 ± 0.213	0.728 ± 0.071	0.670 ± 0.071	0.582 ± 0.048	0.582 ± 0.000	0.625 ± 0.012
SM	0.844 ± 0.024	0.727 ± 0.024	0.654 ± 0.012	0.582 ± 0.000	0.582 ± 0.000	0.567 ± 0.012

3.5 Crop Yield Response to Management Treatments

Stratified straw management systems had higher yields than conventional tillage in most years of the study. The peanut yield statistics presented in Table 5 indicate that the mean yields were 6.46 under CT, 7.88 under NM, 8.58 under TM and 8.68 under SM. On average, peanut yield under NM was around 21.98% better than CT, with TM and SM being 32.82% and 34.37% better, respectively, than CT. Yields of peanut also improved with the passage of time. Under CT, yield rose from 5.7 in 2018 to 8.9 in 2022, while SM increased from 7.3 to 11.1 over the same period. The peanut-yield response to the four cropping treatments as a function of time is shown in Figure 4.

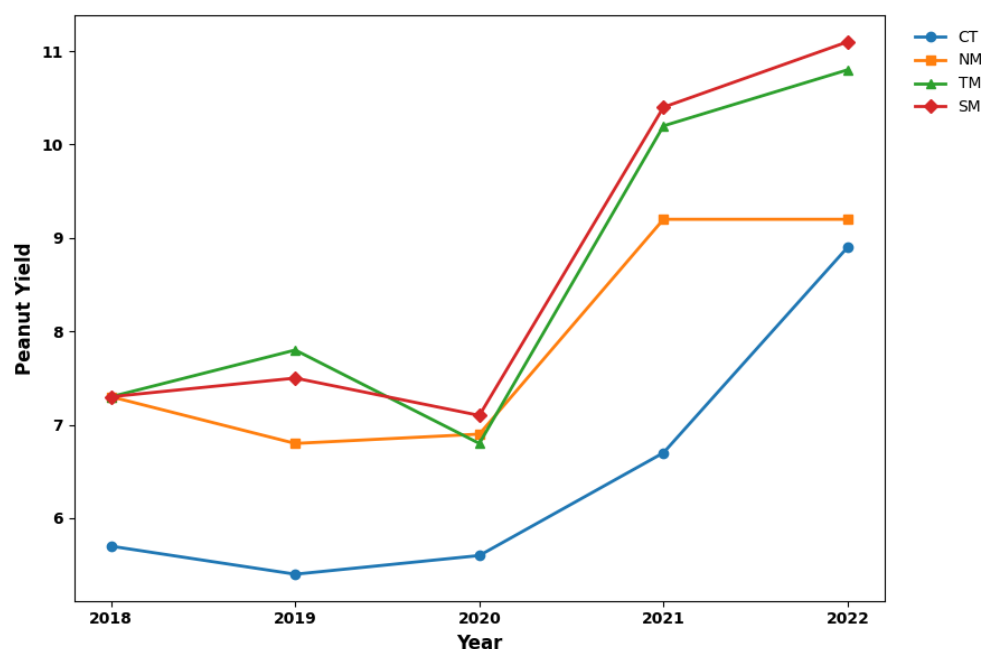


Figure 4. Annual variation in peanut yield under conventional tillage, no-tillage with straw mulching, trench-applied straw mulching, and surface straw mulching from 2018 to 2022

In the same way, rapeseed responded. Mean rapeseed yield was 5.92 under CT, 6.68 under NM, 7.54 under TM, and 7.36 under SM. Relative to CT, the mean yield advantage was 12.84% for NM, 27.36% for TM, and 24.32% for SM. In 2023, rapeseed yield was 9.1 with TM and 9.2 with SM, whereas it was 6.8 with CT. The trend of the increase in rapeseed yield during the experimental period is presented in Figure 5.

Table 5. Annual peanut and rapeseed yields under different management treatments

Crop	Treatment	Year 1	Year 2	Year 3	Year 4	Year 5	Mean yield	Change vs. CT (%)
Peanut	CT	5.7	5.4	5.6	6.7	8.9	6.46	—
Peanut	NM	7.3	6.8	6.9	9.2	9.2	7.88	21.98
Peanut	TM	7.3	7.8	6.8	10.2	10.8	8.58	32.82
Peanut	SM	7.3	7.5	7.1	10.4	11.1	8.68	34.37
Rapeseed	CT	5.1	4.8	6.3	6.6	6.8	5.92	—
Rapeseed	NM	5.4	5.1	7.3	7.7	7.9	6.68	12.84



Rapeseed	TM	6.6	6.1	7.5	8.4	9.1	7.54	27.36
Rapeseed	SM	5.9	5.5	7.4	8.8	9.2	7.36	24.32

Note: Peanut years correspond to 2018–2022, whereas rapeseed years correspond to 2019–2023.

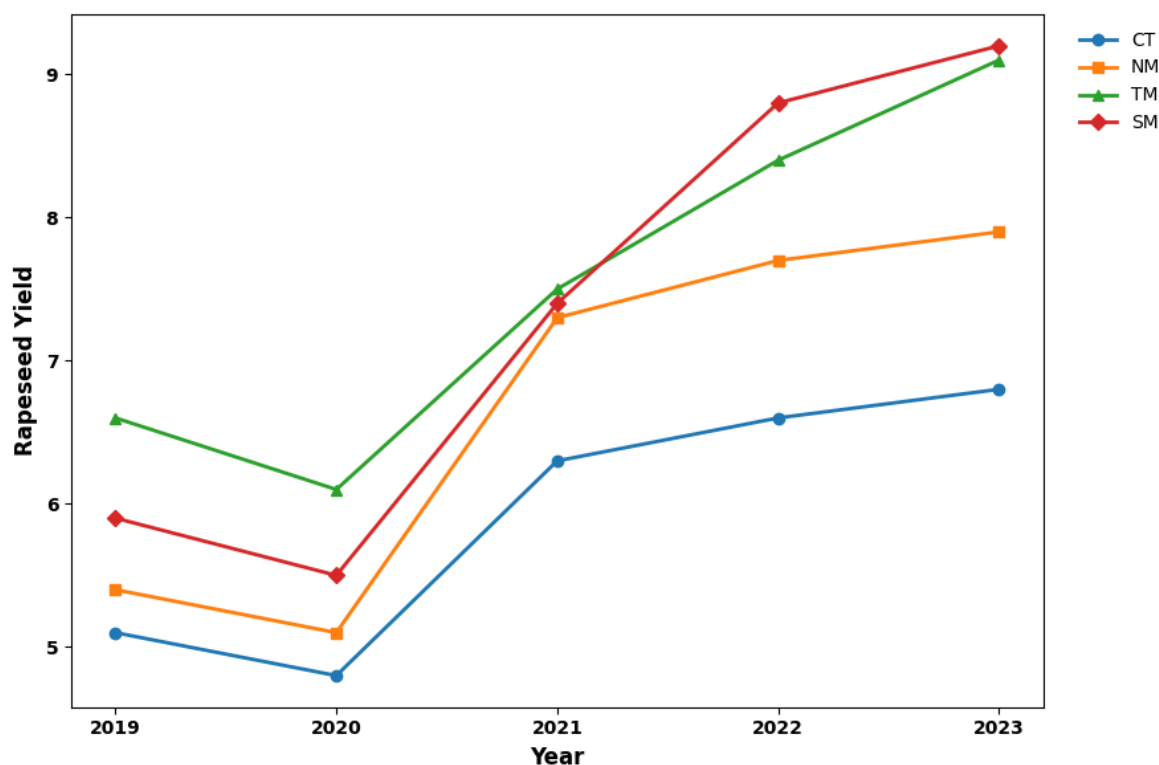


Figure 5. Annual variation in rapeseed yield under conventional tillage, no-tillage with straw mulching, trench-applied straw mulching, and surface straw mulching from 2019 to 2023

3.6 Relationships Between Soil Properties and Soil Quality

The correlation analysis showed high associations between soil quality and some nutrient and structural soil characteristics. As shown in Table 6, SQI was strongly positively correlated with TN at ($r=0.975$), TP at ($r=0.929$), SOC at ($r=0.886$), available phosphorus at ($r=0.843$), and wet-sieved MWD at ($r=0.842$). The water-stable aggregates >0.25 mm and the wet-sieved GMD were also positively correlated with SQI with coefficients of 0.815 and 0.822, respectively.

Sand content, on the other hand, had a strong negative association with SQI ($r=-0.893$), and PAD was also negatively associated with SQI ($r=-0.833$). These relationships suggest that increasing soil quality was correlated with the increased nutrient content and increased aggregate stability, while aggregate destruction and increased sand content were correlated with reduced SQI.

Table 6. Correlation of selected soil properties with soil quality index

Soil indicator	Correlation with SQI, r
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SOC	0.886
TN	0.975
TP	0.929
NH ₄ ⁺ -N	0.841
NO ₃ ⁻ -N	0.773
Available P	0.843
Available K	0.669
Wet MWD	0.842
Wet GMD	0.815
Wet aggregates >0.25 mm	0.822
Sand	-0.893
PAD	-0.833

3.7 Overall Treatment Performance

Overall soil and crop responses indicated that the straw-retaining systems were more successful than the bare soil and conventional tillage systems. The largest MWD, GMD and SQI occurred in NW, and the highest mean peanut yield occurred in SM. The highest MWD, GMD and SQI were obtained in NW, while the highest mean peanut yield was obtained in SM. The values of aggregate-associated SOC and TN were high for TM, which also produced the highest mean yield of rapeseed. The overall results indicate that the straw retention or incorporation under the conditions tested in red cropland led to better soil aggregation, higher nutrient retention, better integrated soil quality and higher yields.

4. Discussion

The present results indicated that tillage and straw-management practices affected soil aggregation; the nutrient contents of the aggregates; overall soil quality; and crop productivity. No-till with straw mulching and surface straw mulching yielded the best structural changes, which resulted in higher water-stable aggregates and lower aggregates less than 0.25 mm. The tendency of this pattern is to maintain the stable formation of macroaggregates by retaining the residue and minimizing disturbance. On the other hand, where long-term straw return was used to boost soil aggregation and make it more difficult for carbon to be captured by the smaller aggregate size, similar responses have been observed (Gan et al., 2022). Larger aggregates can provide physical protection to organic matter and enhance soil pore continuity, which helps to facilitate a good structural function.



The higher mean weight diameter and geometric mean diameter in both the NM and SM also showed improved aggregate stability. In the same vein, percentage aggregate destruction reduced also, suggesting increased resistance to structural breakdown. These results are consistent with straw return under different tillage practices that could improve the stability of soil aggregates and preserve C and N in stable aggregates (Huang et al., 2024). The long-term straw return in situ has also caused the increase of aggregation and aggregate associated organic carbon fractions (Liu et al., 2024). These structural improvements noted here could be due to higher levels of organic binding agents, lower mechanical disturbance, or higher levels of microbial activity in residue-amended soils. The ability to alter soil structure and the degree of stability in yields, however, can vary depending on straw-return method, suggesting the importance of residue placement and tillage intensity as well (Li et al., 2024).

Soil organic carbon and soil total nitrogen also differed between treatments and particle size fractions. Straw mulching when applied to the trenches generated significantly higher concentrations of SOC and TN in some aggregate classes, and higher nutrient concentrations in the NM and SM than in conventional tillage in multiple aggregate classes. The patterns indicate that nutrient protection in aggregates is improved by straw incorporation and retention since more organic substrates are provided and mineralization is slowed down. Straw application and different tillage systems change the SOC composition and microbial communities, which impact the SOC stabilization pathways (Li et al., 2021). The incorporation depth of straw can also influence the yield, SOC, and the total amount of N accumulated in the soil, highlighting the influence of residue placement on nutrient dynamics and productivity (Liu et al., 2021). Buried straw has also been linked to soil physicochemical changes which promote nutrient retention (Yang et al., 2020).

The overall trend of the soil quality index was in a similar direction to the aggregate stability indicators. The SQI values for NM and SM were significantly greater than those for conventional tillage and bare soil and were positively related to SOC, TN, total phosphorus, available phosphorus and wet aggregate stability. On the other hand, there is a negative correlation between PAD and sand content with SQI. These relationships suggest that better soil quality was associated with both the improvement of nutrient status and physical structure. Long-term straw return has been proven to enhance the ecosystem multifunctionality and soil quality, and boost crop yield, as part of this integrated interpretation (Huo et al., 2024). The straw returning can also increase the organic carbon storage, aggregate mix distribution and productivity under the control of nitrogen source (Gao et al., 2023).

The yield response of the crops was similar to that which was obtained with improvement in soil condition. The average yields of peanut and rapeseed were the highest under SM and TM respectively. In general, both crops yielded better with the straw-management treatments than with the conventional tillage. These improvements could be attributed to better aggregation, nutrient retention and better soil physical conditions for root growth and water availability. It has been reported that straw return under deep tillage can increase the grain yield by improving soil condition and resource utilization (Kong et al., 2024); long-term straw return can improve the soil properties and improve the productivity of crops (Li et al., 2023). Meta-analytical studies also show that no-till with straw management can promote soils' carbon sequestration without affecting nutrient availability for the crops (Liu et al., 2023). In general, straw return and tillage influence crop yield, which is affected by tillage-soil carbon, tillage-soil structure response, and local management factors (Zhang et al., 2023).



As a whole, the results suggest that straw-retaining systems had more benefits than other tillage systems, especially NM, SM, and TM, due to improving soil structural stability, nutrient holding ability, soil quality and crop yield. The best treatment did, however, depend on the soil and crop indicator used and thus no one treatment was optimum for all indicators. This is a focus on choosing tillage and straw-management systems based on site, crop needs, and the goal of balancing soil restoration with productivity in extended sustainable agricultural production systems on reclaimed cropland.

5. Conclusion

The present research showed tillage and straw management techniques significantly affect the structural condition of soil, nutrient retention, soil quality and crop production under sustainable agricultural production. The straw-retaining treatments generally obtained better results than those of bare soil and conventional tillage, especially for no-till with straw mulching. The straw-retaining treatments generally showed better results than bare soil and conventional tillage, especially for no-till with straw mulching. The improvements were shown by higher percentage of larger water-stable aggregates, higher mean weight diameter and geometric mean diameter, lower percentage aggregate destruction, and higher soil quality index values. The aggregate associated soil organic carbon and total nitrogen also increased in several size fractions for the straw-based treatments, reflecting increases in nutrient protection and stabilization in soil aggregates. The same trends were observed for crop productivity, with greater mean peanut yield and greater mean rapeseed yield for straw-management systems compared to conventional tillage systems. But the treatment that had the highest response varied depending on the soil and yield indicator assessed, demonstrating the need for assessing management effectiveness for different outcomes. In general, the combination of reduced soil disturbance and judicious application of straw returning practices can promote soil stability, increase carbon and nitrogen retention, and improve soil quality and crop production. The results confirm that adopting tillage and residue management practices that are specific to the site are important for the long-term restoration of the soils, conservation of resources, and sustainable agricultural productivity. This integrated management can thus help to develop resilient cropping systems.

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