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Size and Stability of Soil Aggregates and Organic Matter Content in Soil with Rice Straw Management in Rice-Sunflower Cropping System

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ABSTRACT

Residue management plays a crucial role in enhancing soil organic carbon stabilization by promoting soil aggregation. The current study examined the impact of various residue management practices on soil physico-chemical properties and formation of different sizes aggregates in rice-sunflower cropping system on sandy clay loam soil at Agricultural Research Station, Tornala, Siddipet district, Telangana state during rabi 2022-23 and 2023-24. Compared to residue burning or removal, residue retention followed by zero till Sunflower resulted in an increase in water-stable large macro aggregates, mean weight diameter (MWD), and geometric mean diameter (GMD) by 41.70%, 35.10%, and 17.08% respectively. Residue incorporation treatments increased MWD and GMD by an average of 17.28% and 10.26%, respectively, over the residue-burning treatment. Residue retention followed by zero till Sunflower recorded the highest proportion of >4.75 mm (26.99%) and 4.75-2.00 mm (23.64%) size fractions and the lowest proportions of these fractions were recorded with residue burning with 14.37% and 15.15%, respectively. In contrast, the highest proportions of 2.00–0.5 mm (43.67%) and 0.5–0.25 mm (15.44%) size fractions were observed under residue burning, followed by residue removal + RDF which recorded 41.10% and 14.64%, respectively. Soil organic matter was significantly higher in treatments involving straw incorporation, particularly in those with residue incorporation as such + RDF (T_4-8.20 g kg^{-1}) and C: P ratio adjustments (T_6-8.10 g kg^{-1}).

Keywords: *Rice residue, rice-sunflower, soil aggregates, MWD, GMD, SOM, straw C:N, C: P, C: N: P ratio.*

INTRODUCTION

Rice is the most important staple food crop grown in all regions of India. Rice area, production and productivity in India are approximately 46.4 million hectares (m ha), 135.54 million tonnes (mt) and 2,798 kg ha^{-1}, respectively during 2022. With the increase in the irrigation potential in the state of Telangana, the area under rice during both *kharif* and *rabi* seasons together increased to 42.95 lakh hectares during 2020-21 and in Siddipet district to 2.04 lakh hectares, recording a threefold increase over 2017-18. While this expanded area of the crop contributes to making the state the rice bowl of India, it also brings in its wake potential environmental threats from burning of the huge quantities of residues.

Rice straw is a leftover residue from the harvesting of rice. Farmers have been practicing residue burning to dispose of the residue quickly so as to enable land preparation for the next crop. Rice residues have been traditionally burnt or removed; that is often criticized for losses of soil organic matter, and nutrients, reducing soil microbial activity and increasing CO_2 emission. Among the different crops according to FAO [1] globally, maize (45%) contributes the highest emissions (CO_2 equivalent) through burning of crop–residues, followed by wheat (26%), rice (25%) and sugarcane (4%).

Managing organic matter inputs through the application of organic amendments plays a vital role in improving soil health. Among these, straw incorporation is a widely practiced agricultural method to enhance soil physical properties and nutrient content [2]. Soil aggregation is the process where primary soil particles are bound together to form larger, secondary structures. It is a key physical property. The materials responsible for this binding include iron oxides and hydroxides, organic compounds from plants, decomposed crop residues, microbial cells, by products of microbial activity, and gelatinous substances produced by earthworms. Soil aggregation is vital for maintaining soil fertility by mitigating erosion and regulating air permeability, water infiltration, and nutrient cycling [3] [4]. Soil aggregate stability can be accessed through indicators like GMD (Geometric Mean Diameter) and MWD (Mean Weight Diameter), which directly indicate the cohesion or breakdown of soil particles, as well as their potential for nutrient retention [5]. Various residue management practices directly impact the physical stability of macro-aggregates, thereby influencing soil aggregation. Additionally, changes in biological and chemical components indirectly impact aggregation dynamics. The incorporation of organic residues significantly enhances soil aggregation, which in turn creates a more favourable root environment and promotes overall plant growth.

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The accumulation and turnover of soil organic carbon (SOC) in response to various agricultural practices are closely linked to soil aggregates. These aggregates play a crucial role in protecting and sequestering SOC, with nearly 90% of SOC build-up occurring within them [6]. Soil aggregate size classes provide varying levels of physical protection to associated SOC against microbial decomposition and are influenced by management practices such as tillage and crop residue retention. Organic matter aids in binding soil particles, promoting aggregate formation, while aggregates, in turn, physically protect SOC through encapsulation. Macroaggregates, often used as indicators of tillage-induced changes, play a critical role in protecting SOC and supporting better soil health. Minimum soil disturbance is another option to improve soil structure and promotes biodiversity, both of which are essential for supporting crop growth. This method leads to higher levels of soil organic matter and better water retention, fostering a more fertile environment for crops [7].

Sunflower is the most important oil seed crop. Research has shown that effective soil and residue management can significantly enhance sunflower yields in the country's semi-arid regions. This study aimed to examine the short-term impacts of incorporating rice residues on soil physical properties within the rice-sunflower cropping system under dry land conditions.

MATERIALS AND METHODS

Experimental site

The experiment was conducted in plot no. 19 of "A" block at Agricultural Research Station, Tornala in Siddipet district, Telangana located in Central Telangana Zone. Geographically, the experimental field is positioned at 18°06'35" North latitude and 78° 44'27" East. The soil of the experimental field is sandy clay loam in texture, having 66.40% sand, 8.30% silt, and 25.30% clay.

During the *rabi* season of 2022–23, the mean weekly maximum temperature ranged from 27.71°C to 37.71°C, while the mean weekly minimum temperature ranged from 17.36°C to 24.21°C. In the *rabi* season of 2023–24, the mean weekly maximum temperature varied between 28.07°C and 38.21°C, and the mean weekly minimum temperature ranged from 13.50°C to 26.87°C. The mean annual rainfall of Siddipet district was 784.2 mm in 2022-23 and 753.6 mm, which was mostly received during July–September with occasional rain during winter.

Experimental details

The experiment was laid out in randomized block design (RBD) with seven treatments and three replications during two consecutive years of 2022-23 and 2023-24 during both the *kharif* and *rabi* seasons. Treatments consist *viz.*, T_1: Burning of rice residue 2 weeks after harvesting + RDF, T_2: Rice residue removal + RDF, T_3: Rice residue retention and zero till sowing of sunflower + RDF, T_4: Incorporation of residue as such after harvest + RDF, T_5: Adjusting C-N ratio of residue to 30:1 by applying part of 1st dose of N through urea at the time of incorporation + Remaining RDN in 3 splits and P, K as recommended, T_6: Adjusting the C-P ratio of residue to 30:0.3 by applying part of recommended dose of P through SSP at the time of incorporation + remaining RDP as basal & N, K as recommended and T_7: Adjusting C-N-P ratio of residue to 30:1:0.3 by applying part of 1st dose of N through urea and part of recommended dose of P through SSP at the time of incorporation + Remaining RDN in 3 splits and P, K as recommended. The layout plan for sunflower cultivation remained identical for both seasons, ensuring that the same treatments were applied to the same plots. The net plot size was 8.0 × 7.2 m, while the gross plot size was 57.6 m^2. Urea and SSP were used as sources of nitrogen and phosphorus for the sunflower crop, according to the treatments. Muriate of potash was applied to supply potassium.

Treatment imposition involved quantifying the rice residue/straw (4.214 and 5.186 t ha^{-1}) after the *Kharif* crop harvest. The straw carbon (35.75% and 36.75%), nitrogen (0.65% and 0.71%), and phosphorus (0.17% and 0.22%) contents were analyzed, recording C: N ratios of 55:1 and 51.76:1, C: P ratios of 126:1 and 167.05:1, and C: N: P ratios of 55:126:1 and 51.76:167.05:1 for the 2022-23 and 2023-24 seasons, respectively.

Based on these results, the straw C: N ratio was adjusted to 30:1 before incorporation by applying part of the first dose of nitrogen (284 g and 338 g urea $plot^{-1}$). The C: P ratio was adjusted to 30:0.3 by applying part of the first dose of phosphorus (111.5 g and 275 g SSP $plot^{-1}$). Similarly, the C:N:P ratio was adjusted to 30:1:0.3 using urea (284 g $plot^{-1}$) and SSP (111.5 g $plot^{-1}$) as sources of nitrogen and phosphorus.

For residue incorporation treatments (T_4 to T_7), a rotary mulcher was used to chop the straw, which was then incorporated into the soil using standard tillage operations, including two passes with a cultivator followed by rotation. For treatments involving residue burning or removal (T_1 and T_2), two cultivator passes followed by rotation were performed. In the control treatment (T_3), rice stubble regrowth was controlled by spraying paraquat at 5 ml L^{-1}, the rice residue was retained, and zero-till sunflower sowing was carried out along with the application of the recommended dose of fertilizer (RDF).

The sunflower hybrid DRSH-1, with a maturity period of 90–95 days, was sown at a rate of 2 kg ha^{-1}. Two seeds were manually dibbled per hill, maintaining the recommended spacing of 45 cm × 20 cm.

Soil sample collection and analysis

Soil samples were collected from a depth of 0 to 15 cm using a soil auger at initial and at the end of each cropping cycle during *rabi*, 2022-23 and 2023-24. Composite samples were prepared and air-dried in the shade. One portion of the dried sample was ground and sieved through a 0.5 mm sieve for the determination of organic carbon (OC) content. The other part of the air-dried ungrounded samples were passed through 8 mm and 4.75 mm sieves. The samples on the 4.75 mm sieves were used for estimating aggregate size distribution and the aggregates retained on the 8 mm sieves were discarded.

Mean weight diameter

Soil aggregate analysis was carried out by wet sieving method using Yoder's apparatus [8]. Accurately 50 g of soil was placed on a nest of six sieves of 4.75, 2.0, 1.0, 0.5, 0.25 and 0.15 mm and submerged underwater for 10 minutes. The sieves were oscillated by the pulley for 30 min at a frequency of 30-35 cycles/min in water inside the drum. After shaking for half an hour, the sieves were removed. Soil retained in the 4.75 mm sieve and soil that passed through the 0.15 mm sieve was discarded. The soil in the other sieves was quantitatively transferred to metal boxes and dried in a forced draft hot air oven at 105°C and the weights were recorded. The mean weight diameter (mm) of soil aggregates in the size range of 0.15 to 4.75 mm was determined as:

$$MWD\ (mm) = \sum_{i=1}^{n} XiWi$$

Where W_i is the proportion of each aggregate class in relation to the bulk soil and X_i is the mean diameter of the aggregate class (mm).

Water stable macro and micro aggregates: The macro aggregates were determined by adding the aggregates retained over 0.25– 2.0 mm sieves while the micro aggregates referred to aggregates retained on 0.05–0.25 mm sieves.

$$WSA\% = \frac{[(\text{Weight of soil + sand})^{*}i - (\text{Weight of sand})^{*}i]}{\text{Weight of oven-dried soil}}$$

where i denotes the size of the sieve.

The percentage of water-stable macro aggregates (WSMacA) and water-stable micro aggregates (WSMicA) is the summation of soil aggregate size fractions of > 0.25 mm and < 0.25 mm, respectively. These two were summed up to estimate the total water-stable aggregates.

The geometric mean diameter (GMD) of aggregates was calculated as:

$$GMD\ (mm) = \exp[\frac{\sum_{i=1}^{n} WilogXi}{\sum_{i=1}^{n} Wi}]$$

Where n is the number of fractions (0.1–0.25, 0.25–0.5, 0.5–1.0, 1.0–2.0, > 2.0 mm), *Xi* is the mean diameter (mm) of the sieve size class (0.175, 0.375, 0.75, 1.5 and 2.0 mm) and *Wi* is the weight of soil (g) retained on each sieve.

Soil organic matter

Organic carbon content was determined in 0.5 mm sieved soil samples using the procedure given by Walkley and Black (1934). One gram of soil was taken in 500mL Erlenmeyer flask,10 mL of $K_2Cr_2O_7$ and 20 ml of concentrated H_2SO_4 were added and allowed for digestion for 30 min. To this solution, 100 mL of distilled water followed by a pinch of NaF and a few drops of diphenylamine indicator were added. The contents turn to a violet colour. It was titrated against 0.5N ferrous ammonium sulfate till the colour changed to green. The soil organic matter was obtained by multiplying the SOC with 1.724 (Van Bemmelen factor).

Soil organic matter (%) = SOC (%) X 1.724

RESULTS AND DISCUSSION

Aggregate size distribution

During the *rabi* seasons of 2022-23 and 2023-24, no significant differences in aggregate size distribution were observed across all treatments, irrespective of whether straw was burned, removed, or incorporated before sowing the sunflower crop (figure 1a). However, at harvest, rice residue management practices significantly influenced the distribution of soil aggregate size fractions. The Figure 1b illustrates that significantly higher proportions of aggregate size classes >4.75 mm (26.99%) and 4.75-2.00 mm (23.64%) aggregates were observed under T_3 treatment. This was followed by T_7 treatment with 23.00% and 21.02% respectively, which was on par with T_5 (23.14%, 20.82%), T_6 (21.85%, 19.93%) and T_4 treatments (21.36%, 19.95) compared to T_1 (14.37%, 15.15%) and T_2 treatment (15.49%, 16.12%). In contrast, The proportion of aggregate size classes 2.00-0.5 mm and 0.5-0.25 mm was significantly higher in the T_1 treatment (43.67% and 15.44%, respectively), which was comparable to the T_2 treatment (41.10% and 14.64%, respectively) as presented in figure 1b. The treatments where straw was incorporated, either with or without adjusting the straw's C: N, C: P, or C: N: P ratios to 30: 1, 30: 0.3, and 30: 1: 0.3, were statistically at par with each other. The highest proportion of <0.25 mm aggregates was observed in T_7 treatment with 15.26%, which was comparable to T_4 treatment (14.66%). Meanwhile, the lowest proportion of < 0.25 mm aggregates was recorded in T_3 treatment, with 7.02%. Intensive tillage practices physically disrupt macroaggregates, exposing soil organic matter (SOM) to accelerated microbial decomposition [12]. In contrast, the soil microbial and biochemical environment in zero-tillage (ZT) systems is less oxidative compared to conventional tillage. This aligns with previous findings by Nandan et al [11].

Water stable aggregates

Residue management had a significant impact on the distribution of various soil aggregate size classes, including water-stable micro-aggregates (WsMic), water-stable large macro-aggregates (WsLMac), water-stable small macro-aggregates (WsSMac) as shown in Table 1 & figure 2a and 2b. The T_3 treatment showed a higher percentage WsLMac, compared to T_1 and T_2 treatments. In contrast, water-stable small macro-aggregates (WsSMac) contribution was highest under T_1, followed by T_2. The contribution of WsMic was highest in T_7 (15.26%), comparable to T_4 (14.66%), followed by T_6 (13.31%), and lowest in T_3 (7.02%).

The percentage of WsLMac was highest under T_3 (50.63%), followed by T_7 (44.02%), which was statistically comparable to T_5 (43.96%), T_6 (41.78%), and T_4 (41.31%). The lowest WsLMac percentage was recorded under T_1 (29.52%). In contrast, the percentage of WsSMac was highest under T_1 (59.12%), on par with T_2 (55.74%). Lower percentages of WsSMac were observed in T_7 (40.89%) and T_3 (42.35%). These findings align with Choudhury et al [12] who observed that, applying organic residues in conjunction with either conventional or conservation tillage methods enhances the formation of water-stable aggregates, favouring larger macro aggregates over smaller micro aggregates. The incorporation of organic residues significantly enhances soil aggregation, which in turn creates a more favourable root environment and promotes overall plant growth [5]. During the decomposition of organic matter, the release of polysaccharides and organic acids plays a crucial role in stabilizing these macro aggregates. These compounds remain concentrated near their production sites, and freshly added residues act as nuclei for fungal and microbial growth. Consequently, in the surface layer of soil, residues and soil particles bind together more effectively to form macro aggregates. Zero tillage (ZT) promotes macro aggregation more effectively than conventional tillage (CT). While macro aggregates are prone to oxidation, they serve as vital reservoirs for soil organic carbon (SOC), crucial for carbon sequestration and nutrient availability. Their presence ensures improved aeration and water infiltration in the root zone. Preserving macro aggregates through reduced tillage (RT) and ZT can create a more favourable soil-crop environment for sustained long-term productivity. Zhao et al [13] also reported that straw incorporation enhances organic matter, which in turn leads to lower soil bulk density and reduced soil compaction. This effect is attributed to the organic matter's low bulk density and its ability to improve soil aggregate stability.

Crop residue retention enhances soil aggregation primarily through two mechanisms.

First, it serves as a protective layer against external forces such as raindrops. Second, the decomposition of residues produces substances like polysaccharides, organic acids, and microbial by products, which bind soil particles together to form macro and micro aggregates [6] [14].

Mean Weight Diameter (MWD) and Geometric mean diameter (GMD)

Soil aggregate stability can be accessed through indicators like GMD (Geometric Mean Diameter) and MWD (Mean Weight Diameter), which directly indicate the cohesion or breakdown of soil particles, as well as their potential for nutrient retention. Different residue management practices directly affect the physical integrity of macro-aggregates, thereby influencing soil aggregation. Additionally, changes in biological and chemical components indirectly impact aggregation dynamics. Effective residue management practices also play a crucial role in maintaining soil aggregate stability.

The data presented in Table 2 showed that no significant differences in MWD and GMD were observed among the treatments before sowing of sunflower during the *rabi* seasons of 2022-23 and 2023-24, following the harvest of the *kharif* rice crop and prior to straw incorporation, removal or burning. Among the straw management treatments, T_3 treatment recorded the highest MWD and GMD, followed by T_5, T_6, and T_7, and T_4 at the harvest of the sunflower crop. The pooled analysis of two years of data, as shown in Figure 3, revealed no significant interaction between years and treatments. Therefore, the results were discussed based on the pooled data.

Higher soil aggregation, larger-sized aggregates, and increased GMD and MWD were observed in T_3 treatment. This was followed by T_5, T_6, and T_7, treatments respectively. These treatments showed superior results compared to residue removal or burning practices.

Pooled data of *rabi,* 2022-23 and 2023-24 indicated that, the significantly highest MWD and GMD were recorded at harvest in T_3 treatment with 2.00 mm and 1.03 mm respectively, which was significantly superior over rest of the treatments. Then followed by T_7 with 1.72 mm and 0.93 mm respectively, which was on par with T_5 treatment with 1.67 mm and 0.94 mm, T_6 recorded with 1.65 mm and 0.91 mm respectively, and T_4 treatment with 1.57 mm and 0.90 mm. The T_2 treatment recorded MWD of 1.35 mm and 0.86 mm, in contrast to the residue burning (T_1), which recorded lowest MWD of 1.30 mm and 0.85 mm respectively.

Higher GMD and MWD values signify larger, less susceptible aggregates distributed throughout the soil. This presence of macro-aggregates indicates a stronger soil structure. Key factors in forming and stabilizing these aggregates include binding agents such as soil organic carbon (SOC), microbial biomass, and soil proteins. Generally, macro-aggregates form around fresh SOC, which serves as a crucial carbon source for microbial activity, fostering the production of these binding agents. Incorporating straw can enhance the carbon supply necessary for aggregate formation [2]. Stubble burning degrades soil structure by eliminating organic residues that play a crucial role in soil aggregation and stability [15].

Incorporating rice straw improved the MWD and promoted the formation of macro aggregates by increasing soil organic carbon (SOC), likely due to enhanced microbial activity from the added organic matter. The microbial decomposition of this organic matter and the production of extracellular polysaccharides (EPS) facilitate soil aggregation. These glue like substances serve as binding agents, enhancing the cementation of soil particles. Additionally, fungal hyphae and plant root helps in binding soil particles into aggregates, further increasing MWD. In contrast, the straw-burning treatment led to a reduction in SOC compared to both the straw and control treatments. This decline in SOC under straw burning is likely attributed to the lower carbon input, which may negatively impact soil aggregation [3]. Valzano et al [16] observed that in a direct drilled system, there were no significant differences in aggregate stability between burned and unburned plots, suggesting that burning does not have short term negative effects on certain physical soil properties.

Soil organic matter (SOM)

The data on SOM content presented in Table 5 showed that it was significantly affected by rice residue and nutrient management during both *rabi* 2022-23 and 2023-24. No significant differences in SOM were observed among all treatments, regardless of whether the straw C:N, C:P, or C:N:P ratios were adjusted, during both *rabi* seasons of 2022-23 and 2023-24.

The pooled data on soil OM presented in Table 3 showed that there was no significant interaction between years and treatments. Among the treatments, the straw incorporated treatments either as such or with adjustment of C: N, C: P, C: N: P of straw and zero till treatment were significantly superior over residue burning and residue removal treatments. Higher organic carbon levels were recorded at 45 days after sowing (DAS) in straw incorporation treatments, irrespective of C: N, C: P, or C: N: P ratio adjustments, compared to treatments involving residue burning or removal, where SOM was declined after straw burning treatment. The highest OM was recorded in the T_4 treatment at all growth stages *viz.,*8.28 g kg^{-1}, 8.26 g kg^{-1} and 8.20 g kg^{-1} at sowing, 45 DAS and 90 DAS respectively. It was closely followed by the T_6 treatment, which recorded OM of 8.21 g kg^{-1}, 8.10 g kg^{-1} at sowing, 45 DAS, and 90 DAS, respectively, T_5 treatment with 7.95 g kg^{-1} at sowing, 7.96 g kg^{-1} at 45 DAS and 7.90 g kg^{-1} at 90 DAS and T_7 treatment at all growth stages *viz.,*7.86 g kg^{-1}, 7.72 g kg^{-1} and 7.70 g kg^{-1} at sowing, 45 DAS and 90 DAS respectively. The T_3 treatment recorded 7.80 g kg^{-1} at sowing, 7.80 g kg^{-1}at 45 DAS and 7.77 g kg^{-1} at 90 DAS in contrast to the residue burning and removal methods. The residue burning + RDF (T_1) treatment recorded the lowest OC at sowing, 45 DAS, and harvest, respectively, with values of 7.08 g kg^{-1}, 7.20 g kg^{-1}, and 7.09 g kg^{-1}. On the other hand, SOC in T_2 treatment was 7.38 g kg^{-1} at sowing, 7.37 g kg^{-1} at 45 DAS, and 7.34 g kg^{-1} at 90 DAS, respectively.

Our results are in accordance with [14] and the primary reason for low SOC levels in residue-burned plots is the loss of a portion of SOC as organic acids during the burning process. While, Liu *et al*. (2014) reported that straw return significantly increased SOC concentration by 12.8%, compared to a 5.1% increase observed with no-tillage practices. This suggests that the input of straw derived carbon may further enhance carbon accumulation in arable soils. Crop residues with a higher C: N ratio is resistant to decomposition. In our study, the addition of inorganic nitrogen alongside these residues reduced their C: N ratio, enhancing their decomposability. The time required for microorganisms to lower the C: N ratio of organic residues to an optimal level for mineralization depends on several factors, including climate, application rate, and microbial activity. Residues with high C: N ratios decompose more slowly, leading to increased SOC concentrations in agricultural soils [18]. Memon et al [19] reported a substantial increase in soil organic matter content, rising from 3.08% to 17.07% under treatments where crop residues were incorporated. In contrast, soil organic matter significantly declined in treatments where residues were burned. While paddy straw incorporation, both with and without nitrogen and phosphorus treatments, resulted in significantly higher SOC compared to burning, the maximum increase was observed when nitrogen and phosphorus were applied alongside paddy straw incorporation in the present field study. This aligns with the findings of [20] who also reported increased SOC with residue incorporation. Similarly, Xionghui et al [21] highlighted that combining crop residue with NPK fertilizers enhanced SOC levels, likely due to the transformation of residual carbon into microbial carbon during the decomposition process [22]. In contrast, burning paddy straw destroys beneficial soil microorganisms and fauna while removing substantial organic matter, leading to reduced SOC [23].

Relationships among the GMD, MWD, and soil properties

These findings demonstrated that the MWD exhibited a statistically significant positive correlation with SOM ($p = < 0.05$) (figure 4) at harvest of the crop. Additionally, MWD was strongly and positively associated with %WS large macro aggregates ($p = < 0.001$). Conversely, MWD showed a significant negative correlation with % WS small micro aggregates ($p = < 0.001$). Furthermore, the GMD was found to be positively correlated with SOM ($p \leq 0.01$) and demonstrated a highly significant positive relationship with % WS large macro aggregates ($p \leq 0.001$).

Conclusion

Our study confirms that the treatment involving residue retention + zero tillage + RDF (T_3) is an effective management practice for improving water-stable large macro-aggregates (WsLMac), with a mean weight diameter (MWD) of 2.00 mm and a geometric mean diameter (GMD) of 1.03 mm. The treatment with straw incorporation after adjusting the C: N: P ratio to 30: 1: 0.3 (T_7) resulted in higher water-stable small macro-aggregates (WsSMac) compared to treatments that involved residue burning or removal. Straw incorporation had a significant impact on soil organic matter, with the treatment where straw was incorporated as such + RDF (T_4) recording the highest soil organic carbon at harvest.

SCOPE OF STUDY

Further research is needed to assess the long-term direct and indirect effects of crop residue management under varying climatic and soil conditions, as well as its implications for sustainable agriculture in other rice-based cropping systems.

CONFLICT OF INTEREST

The authors have declared no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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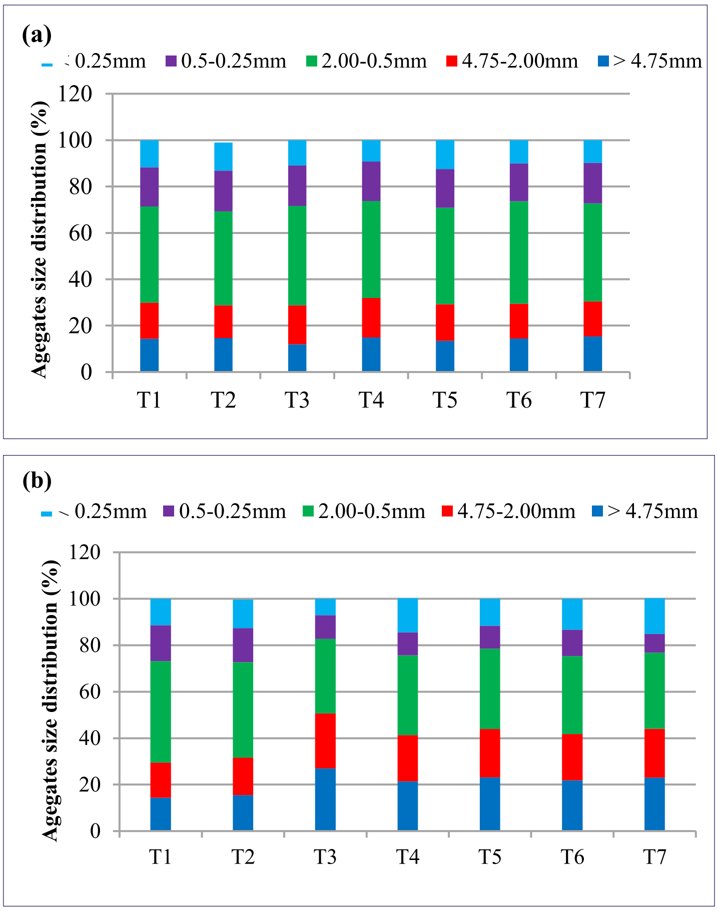


Figure 1. Soil aggregate size distribution (a) before sowing and (b) at harvest of sunflower with rice straw management options

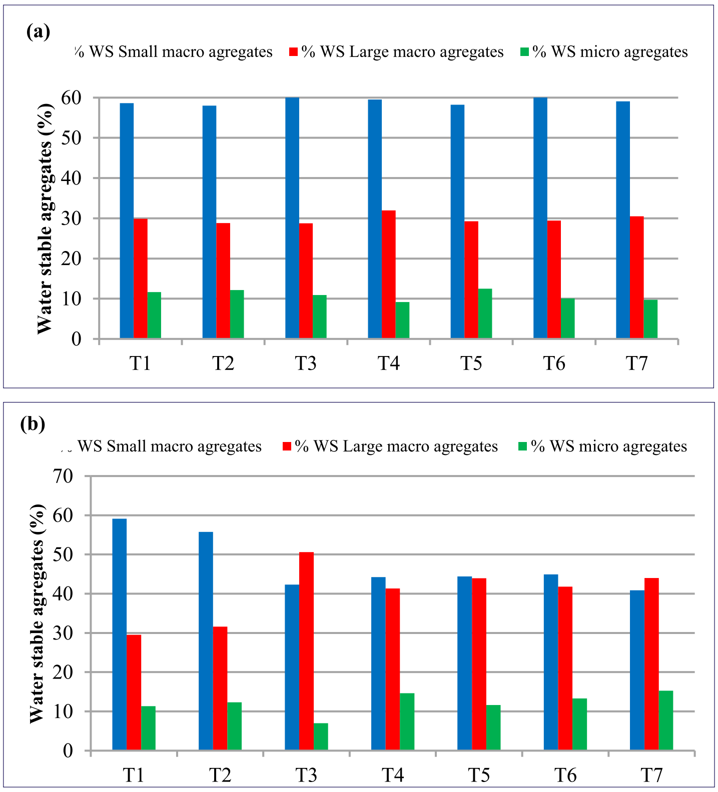
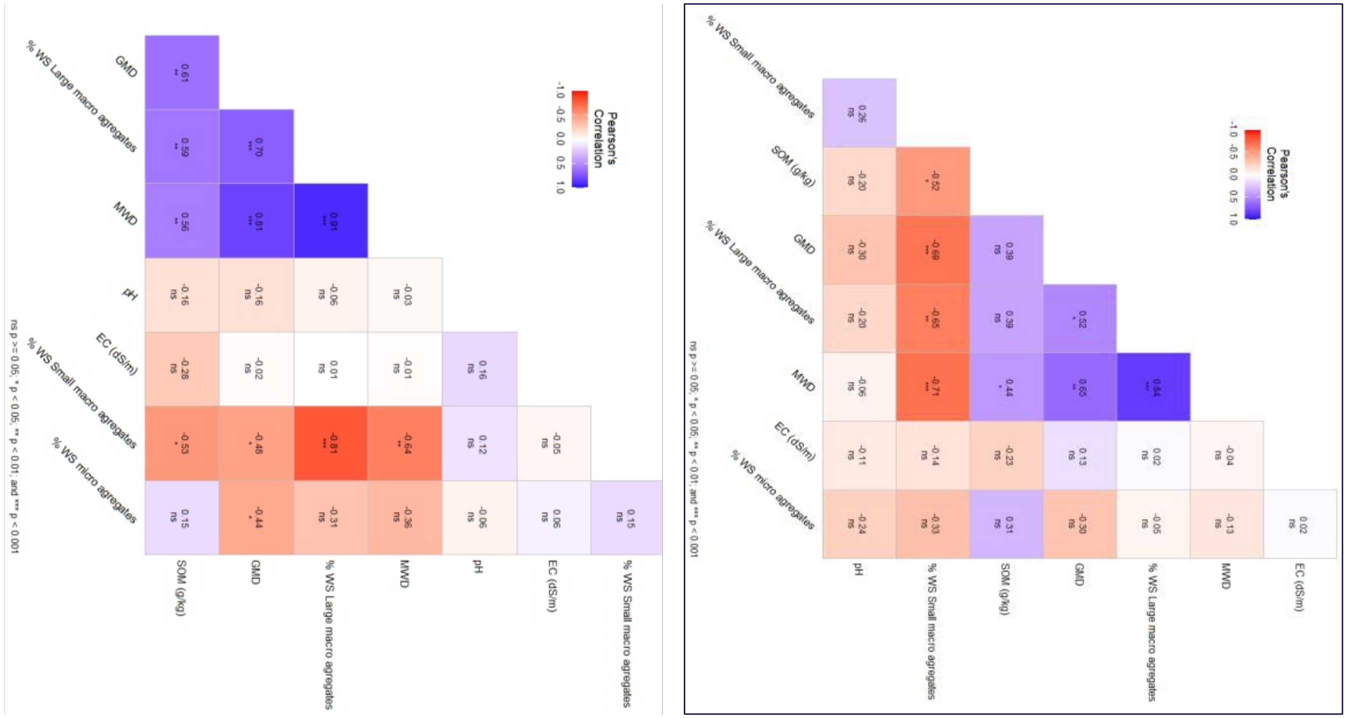


Figure 2. Water-stable aggregates (WsMic, WsLMac and WsSMac), (a) before sowing and (b) at harvest of sunflower with rice straw management options



First year (2022-23) Second year (2023-24)

Figure 4. Person's correlation analysis between geometric mean diameter (GMD), mean weight diameter (MWD), % water stable aggregates, soil pH, EC and soil organic matter (SOM).ns p>=0.05, * P<0.05, ** P<0.01, *** P<0.001

Table 1.Water-stable aggregates (WsMic, WsLMac and WsSMac), before sowing and at harvest of sunflower with rice straw management options

Treatment	% WS Small macro aggregates						% WS Large macro aggregates						% WS micro aggregates					
	Before Sowing/At incorporation			At Harvest			Before Sowing/At incorporation			At Harvest			Before Sowing/At incorporation			At Harvest		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	59.42	57.80	58.61^{a}	59.41	58.83	59.12^{a}	29.47	30.34	29.90^{a}	30.63	28.41	29.52^{c}	11.45	11.86	11.65^{ab}	9.97	12.76	11.37^{b}
T_2	58.48	57.56	58.02^{a}	54.54	56.94	55.74^{a}	29.41	28.25	28.83^{a}	33.57	29.65	31.61^{c}	12.11	12.19	12.15^{ab}	11.88	12.75	12.32^{b}
T_3	61.99	59.25	60.62^{a}	42.01	42.69	42.35^{b}	26.45	31.09	28.77^{a}	50.09	51.17	50.63^{a}	12.23	9.65	10.94^{ab}	7.89	6.14	7.02^{c}
T_4	60.83	58.25	59.54^{a}	44.65	43.85	44.25^{b}	31.59	32.28	31.94^{a}	39.59	43.03	41.31^{b}	8.91	9.47	9.19^{b}	15.76	13.56	14.66^{a}
T_5	58.99	57.48	58.23^{a}	45.22	43.62	44.42^{b}	28.71	29.85	29.28^{a}	42.91	45.01	43.96^{b}	12.30	12.67	12.49^{a}	11.86	11.37	11.62^{b}
T_6	59.49	60.53	60.01^{a}	45.52	44.31	44.91^{b}	29.44	29.43	29.43^{a}	41.54	42.02	41.78^{b}	10.07	10.04	10.06^{ab}	12.94	13.68	13.31^{ab}
T_7	58.78	59.41	59.10^{a}	41.09	40.69	40.89^{b}	30.49	30.47	30.48^{a}	43.51	44.52	44.02^{b}	9.39	10.12	9.76^{ab}	15.40	15.12	15.26^{a}
SE(m)± for years			0.64			0.72			0.62			0.53			0.37			0.29
SE(m)± for treatments	0.78	2.25	1.19	2.05	1.73	1.34	1.69	1.57	1.15	1.45	1.36	0.99	0.88	1.05	0.69	0.56	0.92	0.54
SE(m)± for years X treatments			1.68			1.89			1.63			1.40			0.97			0.76
CD (p=0.05) for years			NS			NS			NS			NS			NS			NS
CD (p=0.05) for treatments	NS	NS	NS	6.31	5.32	3.91	NS	NS	NS	4.46	4.18	2.89	NS	NS	2.00	1.73	2.82	1.57
CD (p=0.05) for years × treatments			NS			NS			NS			NS			NS			NS
CV (%)	2.27	6.64	4.92	7.47	6.33	6.92	9.96	9.01	9.48	6.23	5.79	6.01	13.99	16.74	15.42	7.95	13	10.77

Note: T1: Residue Burning + RDF; T2: Residue Removal+ RDF; T3: Residue Retention + ZT SF +RDF; T4: Residue incorporation as such+ RDF; T5: Adjustment of C:N of residue to 30: 1 before incorporation; T6: Adjustment of C:P of residue to 30: 0.3 before incorporation; T7: Adjustment of C:N:P of residue to 30:1: 0.3 before incorporation.

**Different letters (a-c) denotes significant differences (p<0.05) Duncan Multiple Range Test, OPSTAT.*

Table 2. Mean Weight Diameter and Geometric Mean Diameter before sowing and at harvest of sunflower with rice straw management options

Treatment	Mean Weight Diameter (mm)						Geometric Mean Diameter (mm)					
	Before Sowing/At incorporation			At Harvest			Before Sowing/At incorporation			At Harvest		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1: Residue Burning+ RDF	1.26	1.26	1.26^a	1.32	1.27	1.30^c	0.82	0.83	0.83^a	0.85	0.86	0.85^b
T_2: Residue Removal+ RDF	1.26	1.31	1.28^a	1.39	1.30	1.35^c	0.81	0.82	0.82^a	0.85	0.86	0.86^b
T_3: Residue Retention + ZT SF +RDF	1.09	1.31	1.20^a	1.93	2.07	2.00^a	0.78	0.84	0.81^a	1.02	1.04	1.03^a
T_4: Residue incorporation as such+ RDF	1.25	1.34	1.30^a	1.56	1.57	1.57^b	0.82	0.85	0.84^a	0.89	0.92	0.90^b
T_5: Adjustment of C:N of residue to 30: 1 before incorporation	1.17	1.25	1.21^a	1.68	1.66	1.67^b	0.80	0.82	0.81^a	0.94	0.95	0.94^b
T_6: Adjustment of C:P of residue to 30: 0.3 before incorporation	1.27	1.30	1.28^a	1.65	1.66	1.65^b	0.83	0.84	0.84^a	0.91	0.91	0.91^b
T_7: Adjustment of C:N:P of residue to 30:1: 0.3 before incorporation	1.31	1.38	1.34^a	1.70	1.75	1.72^b	0.84	0.85	0.84^a	0.92	0.94	0.93^b
SE(m)± for years			0.03			0.02			0.009			0.01
SE(m)± for treatments	0.09	0.082	0.06	0.06	0.07	0.05	0.03	0.019	0.017	0.03	0.03	0.02
SE(m)± for years x treatments			0.084			0.07			0.024			0.03
CD (p=0.05) for years			NS			NS			NS			NS
CD (p=0.05) for treatments	NS	NS	NS	0.20	0.21	0.14	NS	NS	NS	0.08	0.10	0.06
CD (p=0.05) for years × treatments			NS			NS			NS			NS
CV (%)	12.41	10.82	11.6	7.01	7.16	7.09	6.16	4.03	5.18	4.91	6.06	5.53

**Different letters (a-c) denotes significant differences (p<0.05) Duncan Multiple Range Test, OPSTAT.*

Table 3. Soil organic matter in soil at different growth stages of sunflower with rice straw management options

Treatment	Soil organic matter (g kg^{-1})											
	At incorporation			At sowing			At 45 DAS			At 90 DAS		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1: Residue Burning+ RDF	7.38	7.22	7.30^a	7.09	7.07	7.08^c	7.21	7.19	7.20^c	7.16	7.01	7.09^c
T_2: Residue Removal+ RDF	7.68	7.33	7.50^a	7.47	7.30	7.38^{bc}	7.34	7.40	7.37^{bc}	7.31	7.37	7.34^{bc}
T_3: Residue Retention + ZT SF +RDF	7.24	7.64	7.44^a	7.61	7.98	7.8^{abc}	7.68	7.92	7.80^{abc}	7.76	7.79	7.77^{abc}
T_4: Residue incorporation as such+ RDF	7.26	7.95	7.60^a	8.26	8.30	8.28^a	8.30	8.21	8.26^a	8.25	8.15	8.20^a
T_5: Adjustment of C:N of residue to 30: 1 before incorporation	7.29	7.74	7.51^a	7.91	7.99	7.95^{ab}	7.86	8.06	7.96^{ab}	7.83	7.97	7.90^{ab}
T_6: Adjustment of C:P of residue to 30: 0.3 before incorporation	7.62	7.79	7.71^a	8.19	8.24	8.21^a	8.07	8.13	8.10^a	8.09	8.10	8.10^{ab}
T_7: Adjustment of C:N:P of residue to 30:1: 0.3 before incorporation	7.52	7.67	7.59^a	7.76	7.96	7.86^{ab}	7.75	7.69	7.72^{ab}	7.67	7.74	7.70^{abc}
SE(m)± for years			0.13			0.09			0.08			0.09
SE(m)± for treatments	0.33	0.35	0.24	0.23	0.23	0.16	0.22	0.22	0.16	0.23	0.24	0.16
SE(m)± for years X treatments			0.34			0.23			0.22			0.23
CD (P=0.05) for years			NS			NS			NS			NS
CD (P=0.05) for treatments	NS	NS	NS	0.70	0.72	0.47	0.67	0.69	0.45	0.69	0.73	0.48
CD (P=0.05) for years × treatments			NS			NS			NS			NS
CV (%)	7.71	7.99	7.86	5.05	5.16	5.11	4.85	4.95	4.90	5.05	5.32	5.18

**Different letters (a-c) denotes significant differences (p<0.05) Duncan Multiple Range Test, OPSTAT.*

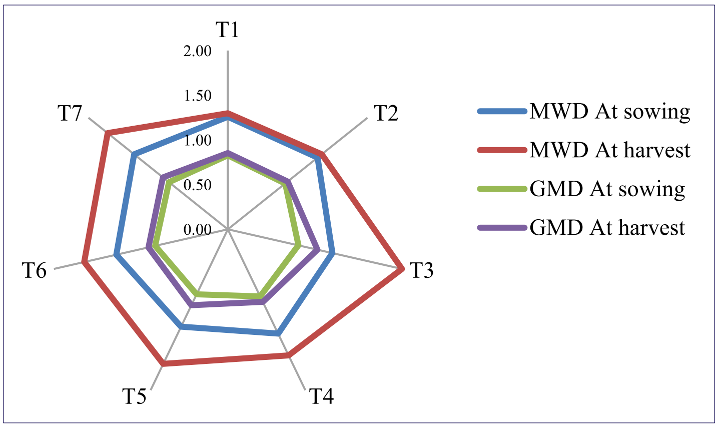


Figure 3. Mean Weight Diameter and Geometric Mean Diameter before sowing and at harvest of sunflower with rice straw management options

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