Soil Quality and System Yield of Cotton-Maize as Influenced by Conservation Agricultural Practices under Semi-Arid Indian Environment

Knight Nthebere
kntheberе@gmail.com

Jayashankar Telangana State Agricultural University
RAM PRAKASH TATA
Jayashankar Telangana State Agricultural University
Padmaja Bhimireddy
Jayashankar Telangana State Agricultural University
Latha P. Chandran
Indian Institute of Rice Research
Jayasree Gudapati
Jayashankar Telangana State Agricultural University
Meena Admala
Jayashankar Telangana State Agricultural University
Nishant Kumar Sinha
Indian Institute of Soil Science
Srikanth B. Thumma
Jayashankar Telangana State Agricultural University
Prasad Kavuru
Indian Institute of Rice Research

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Abstract

Intensive agriculture is the chief cause of soil degradation particularly in regions with low status of soil organic carbon (SOC) as in the semi-arid of southern India. In the quest of attaining sustainable crop yield and improved soil quality, conservation agriculture (CA) is being advocated and adopted globally including India. In this present experiment, CA was implemented to investigate the synergetic impacts of different tillage and weed management practices on soil quality (SQ) and system yield (SY), and to identify remunerative treatment combination (tillage – weed management) which can sustain SY and enhance SQ. Three tillage practices (main plots); **T_1**:CT(C)-CT(M)-fallow(N*Sr*), **T_2**:CT(C)-ZT(M)-ZT(*Sr*) and **T_3**:ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS and weed control tactics involved (sub plots); **W_1**-Chemical weed control, **W_2**-Herbicide rotation (in alternative year), **W_3**- Integrated weed management (IWM) and **W_4**-Single hand-weeded control with cotton-maize-*Sesbania rostrata* cropping system over 3 years. A total of 40 soil variables were analysed at 60 days after sowing (DAS) and after harvest of maize (5th cropping cycle) and subjected to principal component analysis (PCA) in SQI CAL software to choose variables, minimum data set (MDS) and obtain a soil quality index (SQI). The following soil properties; SOC, silt, available Zn, Fe, soil potassium, nitrogen, pH, EC, soil C: N and CEC were selected as indicators based on correlations, calculated PCA and adept opinions on the texture and lime concretions of the experimental soil. The SQI was improved (62.09%) by the adoption of T_3 in combination with W_4 (T_3W_4) followed by T_3 and W_3-IWM (T_3W_3) combination. The system cotton equivalent yield (CEY) was significantly higher (4453 kg ha^{-1}) under T_3 and W_3-IWM (T_3W_3), while significantly lower system CEY was observed under T_3 with W_4 combinations (T_3W_4). So, considering both the system CEY and soil quality, T_3 and W_3-IWM was considered as the best treatment combination among all others for sustenance of both the soil and crop productivity in semi-arid conditions of southern India.

Introduction

Soil, the dynamic living soul, contributes value to humans; however, its potential benefits may be hindered by threats unless properly managed. Soil degradation induced by industrial and urban agricultural practices has triggered land mortification and serves as an anthropogenic cause of food insecurity through climate change (Padbhushan et al., 2022). Since the 1970s, India has been suffering from severe land degradation and high demand for food production due to a surge in population (Suarez et al., 2021; Ansari et al., 2022; Panwar et al., 2022). Such improper agricultural practices result in loss of not only the soil productivity but also results in a decrement in soil's capacity to perform its ecological functions and ecosystem services which ultimately leads to the reduction of soil quality (SQ).

In the light of this challenging context for agriculture, conservation agriculture (CA) has emerged as a promising sustainable farming practice across the entire world in recent decades to sustain the soil resource and crop productivity. CA has been gaining momentum worldwide with the total area of 205 M ha globally in 2022 (Mrabet et al., 2022). It is defined as "a concept for resource-saving agricultural crop production levels while concurrently conserving the environment" (FAO, 2015). This farming practice relies on SQ enhancement based on these precepts; (1) minimum soil disturbance, (2) permanent soil cover through crop residues, and (3) crop rotations with diverse crops for achieving higher production, efficient soil and water conservation, and adequate SOC sequestration (FAO, 2022). FAO presents the slogan of 'Healthy soils for healthy life' during 'International Year of Soils-2015' and put emphasis on soil sustainable management which can be possible only by knowing the health of soil through assessment of its quality (http://www.fao.org/soils-portal/en/). In this context, CA is being promoted in India through the National Mission for Sustainable Agriculture (NMSA) (Pradhan Mantri Krishi Synchayee Yojana-PMKSY).

It may be noted that among other practices within CA, weed control is often achieved through adoption of the latest development; pre- and post-emergence broad-spectrum herbicides due to shortage of labour for weeding, thus maintaining the crop stand and yield same as in conventional production system (Singh *et al.*, 2015). However, these herbicides are known to pose a significant negative effect on the key soil quality parameter indicators (soil biological parameters). Soil quality (SQ) is the key factor in environmentally friendly agriculture such as CA, as it determines crop productivity and soil health. The changes occurring in soil as a result of various agricultural management practices such as tillage and weed control strategies being implemented can be assessed through evaluation of different physico-chemical, chemical, physical and biological soil properties (Duddigan et al., 2023). These soil characteristics aid in qualitative assessment of SQ depending on separate variables. Nevertheless, to contrast the effect of specified agricultural production systems on soil, necessitates a quantitative index as to formulate an assessment thoroughly and deduce whether they are good, poor or moderate (Ponnusamy et al., 2024). Such an index aids in grouping the impacts of cropping practices holistically and to evaluate the development or degeneration inter-linked with soil functions at both local and regional scale. Similarly, to evaluate SQ in each homogeneous soil type with same climatic conditions and under contrasting cropping systems and management practices, an index should be generated capable of construing the existing SQ or lack thereof into computable categories (Ponnusamy et al., 2024).

A quantitative evaluation technique is the Soil Quality Index (SQI), which is an optimal logic method to find out whether SQ values rises, stays the same or declines under contrastive cropping practices (Masto et al. 2007). Several studies conducted across the globe and in India have reported that adoption of no-till (NT) with retention of crop residues under diversified crop rotations has significantly improved soil biological quality, soil chemical quality, soil physical quality and SQI in comparison with conventional tillage systems (Aziz et al., 2013; Choudhary et al., 2018a; Kumar et al., 2017; Roy et al., 2022). In spite of the fact that the effects of conservation agriculture (CA) on soil quality, agro-ecosystem services and crop yield have been explored at global level and in India, there is scanty information on the synergetic impact of tillage and weed management practices in CA on soil quality (SQ) enhancement and the potential gains worldwide including Southern Telangana State (STS) of India. Thus, this current investigation has been implemented to identify a remunerative tillage and weed management combinations for sustaining the crop productivity and improving the SQ, and to assess the synergetic effects of different tillage practices and weed management options in CA on soil quality and the overall impact on cotton-maize productivity under cotton-maize-*Sesbania rostrata* cropping system over three years in the semi-arid regions of STS of India.

Material and methods

Details of the experiment

This current field study was conducted at the College Farm, PJTSAU, Southern Telangana Zone of India, under the All India Coordinated Research Project (AICRP) on Weed Management. The field trial is located at 16^0 18' 17" N latitude and 78^0 25' 38" E longitude. The satellite outlook of the field is presented in Figure Supplementary 1. The field experiment was implemented from 2020–2021 in the monsoon, winter and summer seasons under cotton (*Gossypium hirsutum*), maize (*Zea mays*), and green manure (*Sesbania rostrata*) rotations, respectively. The experiment continued from 2020–2021 until 2022–2023, without disturbing the field layout in the same site. The month wise Meteorological observations taken on weekly basis during the crop development from the station situated at the Institute of Agricultural Research (IAR), Rajendranagar are presented in Figure Supplementary 2 and 3.

The soil samples were collected prior to the commencement of the experiment in 2020–2021, processed and characterized with respect to different soil attributes. It is taxonomically classified under the soil order *Inceptisol*, sandy clay loam (66.00% sand, 21.40% clay and 12.60% silt), CEC (21.54 cmol (p+) kg^{-1}), slightly alkaline (7.82) in pH, non-saline (0.33 dS m^{-1}), medium content of soil organic carbon (6.50 g kg^{-1}) and available soil phosphorus (22.40 g kg^{-1}), low content of available soil nitrogen (220.90 kg ha^{-1}), and high content of available soil potassium (408.75 kg ha^{-1}) status in the 0–15 cm. The surface (0–15 cm) micronutrients content *viz.*, Fe, Mn, Zn and Cu were 12.50, 5.57, 1.58 and 0.80 mg kg^{-1} respectively, and were all above the critical limits. The soil bulk density was 1.23 Mg m-3 in the 0–15 cm and 1.30 Mg m-3 in the 15–30 cm. Soil penetration resistance was 1.17 and 1.73 MPa in the 0–15 cm and 15–30 cm, respectively. The surface (0–15 cm) maximum water holding capacity, mean weight diameter, infiltration rate and saturated hydraulic conductivity was 43.80%, 0.79 mm, 1.22 cm hr^{-1} and 1.28 cm hr^{-1}, respectively.

Design of the experiment and treatment details

A conservation agriculture (CA) experiment was conducted in accordance with a split plot design with three tillage (s) practices in the main plots, as shown in Table 1; four weed management options in the sub-plots as detailed in Table 2; and treatment combinations of tillage and weed management were replicated thrice. For T_1, which was subjected to conventional tillage, the plots were prepared by ploughing two times, followed by rotovating and seeding. In T_2, no-till of the soil (*Z*ero tillage- ZT) *i.e.*, seeding was done directly by opening the soil followed by surface soil sealing, and in T_3, there was ZT (cotton) + *Sesbania rostrata* residues (*Sr*R) in monsoon – ZT (maize) + cotton residues (CR) in winter – ZT (*Sesbania rostrata*) + maize stubbles (MS) (*i.e.*, *Sesbania rostrata* was sown adjacent to maize stubbles) in summer. The succeeding crops (cotton and *Sesbania rostrata*) residues were shredded and retained (as surface mulch), and seeding was performed directly by opening the soil, accompanied by surface sealing with mulch from crop residues (Table 1).

The cumulative mean annual input of organic biomass/residues from cotton and *Sesbania rosrata* retained in T_3 plots, since the year 2020–2023, was about 200.0 to 240.0 Mg ha^{-1}, estimated according to Bolinder et al. (2007). The weed management strategies used included: W_1: chemical weed control, W_2: herbicide rotation, W_3: integrated weed management (IWM) and W_4: single hand-weeded control, as fully described in Table 2. No tillage operations or weed management were implemented prior to sowing of summer *Sesbania rostrata*, as it was cultivated up to 45 days to be retained and cover the soil in T_3. There was no *Sesbania rostrata* sown in the T_1 plots; *i.e.*, the plots were fallowed during the summer season.

Table 1
Annotation of tillage treatments with crop diversification in the main plots

Tillage (s)	**Seasons**		
	Monsoon	**Winter**	**Summer**
T_1 :	CT (C) –	CT (M) –	Fallow (N*Sr*)
T_2 :	CT (C) –	ZT (M) –	ZT (*Sr*)
T_3 :	ZT(C) + *Sr*R –	ZT (M) + CR –	ZT (*Sr*) + MS

CT(C) = conventional tillage (cotton), ZT(M) = zero tillage (maize), Fallow (N*Sr*) = Fallow(No *Sesbania rostrata*), ZT(*Sr*) = zero tillage (*Sesbania rostrata*), ZT(C) + *Sr* = zero tillage (cotton) + *Sesbania rostrata* residues, ZT (M) + CR = zero tillag (Maize) + cotton residues, ZT (*Sr*) + MS = zero tillage (*Sesbania rostrata*) + maize stubbles.

Table 2
Weed management (W) in sub-treatments and interaction with tillage (T) in main treatments

	Monsoon (Cotton)				Winter (Maize)			
	W_1: Chemical Weed Control	W_2: Herbicide Rotation (Alternative year)	W_3: IWM	W_4: Single hand-weeded Control	W_1: Chemical Weed Control	W_2: Herbicide Rotation (Alternative year)	W_3: IWM	W_4: Single hand-weeded Control
T_1	Diuron pre-emergence (PE) application 0.75 kg/ha *fb* tank mix appli-cation of pyrithiobac -sodium 62.5 g/ha + quizalofop-ethyl 50 g/ha as PoE (Post-emergence application) (2–3 weed leaf stage) *fb* directed spray (inter-row) of paraquat 0.5 kg/ha at 50–55 DAS.	Diuron PE 0.75 kg/ha *fb* tank mix application of pyrithiobac-sodium 62.5 g/ha + quizalofop-ethyl 50 g/ha as PoE (2–3 weed leaf stage) *fb* directed spray (inter-row) of paraquat 0.5 kg/ha at 50–55 DAS. **rotated with** Pendimethalin 1 kg ha^{-1} *fb* tank mix application of pyrithiobac-sodium 62.5 g/ha + quizalofop ethyl 50 g/ha as PoE (2–3 weed leaf stage) *fb* directed spray (inter-row) of paraquat 24% SL 0.5 kg/ha at 55 DAS.	Diuron PE 0.75 kg/ha *fb* mechanical brush cutter twice at 25 and 60 DAS.	One hand weeding was done after the critical period of crop-weed competition *i.e.* between 45–50 days after sowing).	Atrazine 1.0 kg/ha + paraquat 600 g/ha PE *fb* tembotrione 120 g/ha at 20–25 DAS as PoE (T_2, T_3). Atrazine 1 kg ha^{-1} PE *fb* tembotrione 120g/ha at 20–25 DAS as PoE (T_1).	Atrazine 1.0 kg/ha + paraquat 600 g/ha PE *fb* tembotrione 120 g/ha at 20–25 DAS as PoE (T_2, T_3). Atrazine 1.0 kg/ha PE *fb* tembotrione 120g/ha at 20–25 DAS at PoE (T_1). **rotated with** Atrazine 1.0 kg/ha + paraquat 600 g/ha PE *fb* halosulfuron-methyl 67.5 g/ha at 20–25 DAS as PoE (T_2, T_3). Atrazine 1.0 kg/ha PE *fb* halosulfuron methyl 67.5 g/ha at 20–25 DAS as PoE (T_1).	Tembotrione 120 g/ha & Atrazine 50% WP 0.5 kg/ha both applied as early post-emergence) EPoE *fb* brush cutter at 40 DAS.	One hand weeding was done after the critical period of crop-weed competition *i.e.* between 45–50 days after sowing).
T_2								
T_3								

T_1 = conventional tillage (cotton) – conventional tillage (maize) – Fallow (No *Sesbania rostrata*), T_2 = conventional tillage (cotton) – zero tillage (maize) – zero tillage (*Sesbania rostrata*), T_3 = zero tillage (cotton) + *Sesbania rostrata* residues (*Sr*R) – zero tillage (maize) + cotton residues (CR) – zero tillage (*Sesbania rostrata*) + maize stubbles (MS), IWM = integrated weed management.

Crop management practices

Sowing and fertilizer application

The experimental particulars and characteristics of cotton, maize and *Sesbania* cultivars used are presented in supplementary Tables 1 and 2, respectively. Prior to seeding of cotton and maize, the experimental plots were ploughed two times accompanied by rotovating and levelling with the hand-raking in T_1 plots, while in ZT plots, the seeds were dibbled. *Sesbania* seeds were directly sown in a solid row spacing of 30 cm, positioned in between the maize stubbles. Conversely, in the T_1 plots, no sowing of *Sesbania* took place, and these plots had undergone a short summer fallow period. This distinction in management practices reflects the specific treatments applied to each plot in the experimental design. The recommended doses of fertilizer (RDF) were applied in the form of urea, di-ammonium phosphate (DAP) and muriate of potash (MOP) to raise cotton and maize. RDF for cotton was 120-60-60 kg ha^{-1} of N-P_2O_5-K_2O RDF and was applied in the form of DAP as basal after crop emergence in T_1, T_2 and T_3, urea at 30 days after sowing (DAS), flowering stage (60 DAS) and square formation stages of cotton in equal splits. Advocated doses of fertilizers (ADFs) for maize was N-P_2O_5-K_2O (200:60:50 kg ha-▯). Urea and DAP in maize were split thrice as basal, at knee height and at tasseling period (60 DAS). No fertilizer was applied to for *Sesbania*. Cotton and maize were raised duly following cultural operations and typically developed with rainfall in monsoon and supplemental irrigation in winter due to scanty rainfall.

Soil analysis

Sampling and standard analytical procedures

Soil physico-chemical, chemical and/ or fertility properties

Composite soil samples were randomly collected at different spots in triplicate from each treatment plot established under conservation agriculture at the depth of 0–15 cm and 15–30 cm (based on the parameter under estimation) after harvest of maize crop in the 5th cycle (2022–2023). These collected soil samples were air-dried well under shade, processed through a wooden hammer and passed through 0.5 mm (for soil organic carbon) and 2mm sieve, labelled and stored in polythene covers to be analysed for different physical, physico-chemical chemical/ fertility properties of the soil by duly following the standard procedures (Tables 1 and 2).

Soil biological properties

Rhizosphere samples were collected at tasseling stage *i.e.*, 60 days after sowing (DAS) of maize crop (5th crop cycle) in 2022-23. These samples which were taken from respective plots at different spots, were homogenized, kept in polythene bags with zippers to the laboratory, passed through 2 mm sieve and analysed on the same day as collected from the field for soil microbial population, enzyme activity and microbial activity (Table 3) by duly following the standard protocols. Soil water content was determined according to Wu et al. (2010), and the information was utilized in calculating the evaluated soil biological parameters.

Table 1
Soil physical properties

S. No	Soil property	Method	Reference
Mechanical separates			
1	Sand	Hydrometer method	Bouyoucos (1927)
	Silt		
	Clay		
	Textural class		
2	Mean weight diameter	Wet sieving method	Yoder’s (1936)
3	Bulk density (Mg m^{-3})	Core sampler method	Blake and Hartge (1986)
4	Hydraulic conductivity (cm hr^{-1})	Constant head method	Klute and Driksen (1986)
7	Soil Penetration resistance	Cone Penetrometer	Anderson et al. (1980)
8	Infiltration rate	Double ring infiltrometer	Bouwer (1986)
9	Water holding capacity (%)	Keen’s Raczkowski cup	Keen and Raczkowski (1921)

Table 2
Soil physico-chemical, chemical/ and fertility properties

S. No	Soil property	Method	Reference
1	pH	Soil: water suspension (1: 2.5)	Jackson (1973)
2	EC		Jackson (1973)
3	CEC	Sodium acetate method	Bower et al. (1952)
4	Organic carbon	Wet oxidation method	Walkley and Black (1934)
5	Available Nitrogen	Alkaline $KMnO_4$ method	Subbiah and Asija (1956)
6	Available P_2O_5	Olsen's method for extraction and ascorbic acid	Olsen *et al*. (1954)
7	Available K_2O	Neutral normal ammonium acetate method	Jackson (1973)
8	Cu	DTPA extraction method using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)	Lindsay and Norvell (1978)
	Fe		
	Mn		
	Zn		
9	Organic carbon pools	Modified Walkley and Black	Chan *et al*. (2001)
10	Total organic carbon	Modified Walkley and Black	Jha et al. (2014)
C: N of the soil			
11	Total carbon	Dry ashing	Dean (1974)
12	Total nitrogen	Micro-Kjeldahl	Bremner and Mulvaney (1982)

Table 3
Soil biological properties

Enumeration of soil microbial population				
S. No	**Microorganism**	**Method**	**Reference**	**Growth Medium**
1	Diazotrophs			
	a. *Azospirillum*	Most probable number	Dobereiner et al. (1976)	Sodium malate semi- solid medium
	b. *Azotobacter*	Serial dilution pour	Jensen (1951)	Nitrogen free medium
2	Bacteria		Thorton (1922)	Nutrient agar
3	Fungi		Martin (1950)	Martins Rose-Bengal agar
4	Actinomycetes		Allen (1957)	Ken Knight and Munair's media
Soil enzyme activity				
S. No	**Enzyme (s)**	**Measured by**		**Reference**
1	Urease	Titrimetry		Tabatabai and Bremner (1972)
Phosphatases				
2	Acid	Spectrophotometry		Tabatabai and Bremner (1969)
	Alkaline	Spectrophotometry		Eivazi and Tabatabai (1977)
3	Fluorescein Di-acetate	Spectrophotometry		Green et al. (2006)
4	Dehydrogenase	Spectrophotometry		Casida et al. (1964)
5	β-galactosidase	Spectrophotometry		Eivazi and Tabatabai, 1988)
Soil microbial activities				
Microbial biomass				
1	Biomass carbon	CH_3Cl fumigation extraction method		Beck et al. (1997) and Witt et al. (2000).
2	Biomass nitrogen	CH_3Cl fumigation extraction method		Brookes et al. (1985a, b) Amato and Ladd (1988)
3	Soil basal respiration	Alkali trap method		Da-Silva et al. (2007)

Computation of soil quality index (SQI)

The effect of tillage and weed management practices in conservation agriculture (CA) on soil quality was assessed by weighted index method with SQI CAL software-A Tool for Soil Health Assessment developed by Mohanty (2020). This tool is based on principal component analysis (PCA) methodologies (Mukherjee and Lal, 2014). The input data required for the SQI computation was arranged in CSV format, uploaded in SQI CAL software and principal component analysis was calculated from the input data according to the flow chart presented in Fig. 1. Eigen values, Eigen vectors, PCA cord and PCA contribution were generated from the data calculated by the PCA. Eigen values greater than one were selected and arranged separately. Based on eigen values and factor loadings on each principal component (PC) estimated by PCA and the correlation between the analysed soil properties, variable selection from calculated PCA (+/- of 10%) and minimum data set (MDS) was selected to avoid redundancy (Panwar et al., 2022; Singh et al., 2013). The selected variable indicators were scored according to homothetic linear transformations based on three properties; a. less is better, b. more is better and c. optimum is better (Table supplementary 3) and weighted based on the percentage of variance explained by the indicators on respective PCs to the cumulative variance of all the PCs considered for variable and MDS selection. Finally, SQI_{PCA} was calculated according to Eq. 1, using the updated weight and scoring output as under;

$$SQI_{PCA} = \sum_{i=1}^{n} SixWi$$

where, *Si* is the linear score of each indicator and Wi is the calculated weight factor.

Crop Productivity

The yield of seed cotton and maize grain were recorded after harvest in monsoon (2022) and winter (2022-23), respectively. For cotton, the total seed cotton was harvested in three pickings at weekly interval from each net plot according to the treatments, pooled, weight separately and expressed in kg ha^{-1}. The sum of seed cotton per plot picked at different pickings together with yield of tagged plants and bolls was taken as seed cotton yield per plot and expressed in kg ha^{-1}. Subsequent to harvesting of seed cotton, the stalks of cotton from each net plot was cut above-ground and air-dried. The weight was recorded, converted and expressed in kg ha^{-1}. For maize, grain yield in each net plot was recorded by weighing oven-dried produce at 14% moisture level before threshing and expressed in kg ha^{-1}. The maize stover in the net plot area was cut and the air-dried weight was expressed in kg ha^{-1}. The system yield was computed in terms of cotton equivalent yield (CEY) using the Eq. 2, as under:

$$\text{System CEY (kg ha}^{-1}\text{)} = \begin{array}{c}\text{Economical yield}\\ \text{of a maize crop}\\ \text{(kg ha}^{-1}\text{)}\end{array} \times \frac{\text{Price (Rs kg}^{-1}\text{) of same crop } \textit{i.e.}\text{, maize}}{\text{Price (Rs kg}^{-1}\text{) of cotton}} \qquad (2)$$

Statistical analysis

The data were analyzed statistically applying the analysis of variance technique dully following the ANOVA for split plot design as suggested by Panse and Sukhatme (1978). Critical difference for examining the treatment means for their significance at 5% probability level was performed by Duncan multiple rank test (DMRT). Pearson's correlation coefficients for evaluating the relationship among soil attributes and the PCA for selecting the variable indicators as well as the minimum dataset (MDS) were done by using SQI CAL online software (Mohanty, 2020).

Results and Discussions

Soil physical attributes

The alterations in soil physical characteristics at the end of third year (5th maize crop cycle) were significantly influenced by adoption of different tillage practices (Table 4). While all these soil physical properties were relatable depending on contrastive tillage systems, the proportion of sand, silt and clay remained significantly unchanged by tillage methods. There was no significant impact observed by weed management tactics on overall physical properties. The treatment interaction effects were also non-significant on these properties (Table 4). Among the tillage practices, the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS was observed with the significant enhancement in all the physical properties (bulk density, soil penetration resistance, saturated hydraulic conductivity, infiltration rate, maximum water holding capacity and mean weight diameter) (Table 4). This improvement might be brought by continuous retention of the crop residues, minimal soil disturbance complementary to the crop's deep rooting system, which resulted in more addition of soil organic matter (SOM) in the soil through the decomposition of crop biomass and improved aggregation. The presence of the root pieces in conjunction with crop residues in the soil play a key role and are considered as the primary binding agents through the release of polysaccharide compounds during the decomposition, which in turn contribute in the formation of macroaggregates and enhanced overall soil physical attributes (Six et al., 2000; Bandyopadhyay et al., 2010; Choudhury et al., 2014). Boogar et al. (2014) and Nthebere et al. (2023a) also reported positive effects of adopting conservation tillage (minimum or no-till) on the formation of more stable aggregates and improved physical properties.

Soil physico-chemical, chemical and/or fertility attributes

The imposed tillage and weed management practices did not significantly affect the physico-chemical properties analyzed after harvest of maize (5th crop cycle) except soil organic carbon (SOC) which demonstrated a significant change influenced by different tillage practices. Significantly higher SOC content (7.92 g kg^{-1}) was obtained when the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS was adopted over three consecutive years (Table 4). Fertility properties of the soil *viz.*, macro-nutrients (N, P: P_2O_5, K: K_2O) and micronutrients (Mn, Fe, Zn, Cu) were significantly influenced by tillage methods except available soil K (K_2O), Zn and Cu (Table 4). Similarly, the soil chemical attributes *viz.*, soil C: N, active (C_{ACT}) and passive (C_{PSV}) pools of soil organic carbon) were significantly affected by different kinds of tillage adopted. Among tillage systems, the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS had maximum content of total organic carbon (TOC), macro- and micronutrients, active carbon pool (C_{ACT}), passive carbon pool (C_{PSV}) and wider soil C: N (Table 4). This could be due to the addition of crop residues in the soil through retention which contributed significantly to soil organic matter (SOM) and maintained the plant nutrient availability. Further, less soil disturbance protects the SOC content from adverse environmental factors, leading to more stable aggregates formation which in turn yield SOM, hence an increase in soil nutrient availability (Sapre et al., 2019; Nthebere et al., 2023b). The cotton residues retained and the left-overs of maize stubbles post-harvest in the plots could not have been fully decomposed, thus increasing the soil C: N. This is probably due to a wider C: N of both cotton residues and maize stubbles which slow-down the rate of decomposition due to high energy demand for microbes. The rate of decomposition of added crop residues influences the nutrient cycling (particularly N), and thus impact the availability of nitrogen to plants. Generally, when residues with a wider C: N are retained into the soil, immobilization of N will occur in which the succeeding crop will show N deficiency.

Soil biological attributes

Adoption of ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS and Single hand-weeded control, followed by IWM significantly improved the overall soil biological properties which showed a decreasing trend under such treatments (Table 4). Tillage and weed management interaction effects on biological characteristics of the soil were significantly higher under ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with Singe hand-weeded control and IWM (Table supplementary 4 a, b). These improvements observed under ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS, single hand-weeded control, IWM and their combinations could probably be due to ample additive-free materials drawn from the crops which become a vital component for rapid metabolic reaction to external sources of carbon, thus facilitating soil microbiomes to utilize large quantities of additive-free substrates for proliferation in lieu of respiration purpose. Additionally, the availability of energy and nutrient resources and the limited oxidation of soil organic carbon, favoured by the prevalence of soil microorganisms, likely contributed to this observed enhancement.

Table 4: Impact of tillage practices and weed management options on soil properties during and after harvest of winter maize in the 5th cycle (2022-23).

Continued.

T_1 = conventional tillage (cotton) – conventional tillage (maize) – Fallow (No *Sesbania rostrata*), T_2 = conventional tillage (cotton) – zero tillage (maize) – zero tillage (*Sesbania rostrata*), T_3= zero tillage (cotton) + *Sesbania rostrata* residues (*Sr*R) – zero tillage (maize) + cotton residues (CR) – zero tillage (*Sesbania rostrata*) + maize stubbles (MS); W_3 = Integrated Weed Management (IWM); BD=bulk density, SPR= soil penetration resistance, MWHC= maximum waiter holding capacity, MWD= mean weight diameter, IR= infiltration rate, SHC= saturated hydraulic conductivity, EC= electrical conductivity, CEC= cation exchange capacity, SOC= soil organic carbon, Soil C: N= soil carbon to nitrogen ratio, Avail_N= available soil nitrogen, Avail_P= available soil phosphorus, Avail_K= available soil potassium, Avail_Mn= available soil manganese, Avail_Fe= available soil iron, Avail_Cu= available soil copper, Avail_ Zn = available soil Zn, C_{ACT} pool= active carbon pool, C_{PSV} pool= passive carbon pool, TOC= total organic carbon, DHA= dehydrogenase activity, SUA= soil urease activity, FDA= fluorescein di-acetate activity, AlPA= alkaline phosphatase activity, AcPA= acid phosphatase activity, β-GaA= β-Galactosidase activity, *Azot*= *Azotobacter*, *Azosp*= *Azospirillum*, CFU= colony forming units, SMBC= soil microbial biomass carbon, SMBN= soil microbial biomass nitrogen, SBR= soil basal respiration, qCO_2= metabolic quotient

Minimum dataset (MDS) selection

Subsequent to the assessment of the effect of tillage practices and weed management options on analyzed soil quality parameters, the data was utilized to calculate the soil quality indices as to ascertain the performance of the treatments in maintaining soil quality. A considerable data sets (40 variables) were subjected to principal component analysis (PCA), of which 27 variables were selected. As numerous data sets are dependent, the indicators or MDS were selected based on PCA and correlation among the soil parameters. The details of the soil parameters which are considered, correlated and the calculated PCA are presented in Table supplementary 4 and Table 5, respectively.

PCA was run to select the soil indicators for MDS, and it resulted in seven principal components (PCs) with eigen values > 1.0 which together explained 95.76% variability in the data set. PC1, PC2, PC3, PC4, PC5, PC6 and PC7 explained 63.37, 9.15, 7.60, 4.97, 4.47, 3.18 and 3.02% variations, respectively (Table 5). In PC1, 18 variables were qualified whereas, in PC2, PC3, PC4, PC5, PC6 and PC7, only 2, 2, 1, 1, 1 and 2 variables were qualified, respectively (Table 6). In PC1; mean weight diameter (MWD), soil penetration resistance (SPR), infiltration rate (IR), organic carbon (OC), active carbon pool (C_{ACT}–pool), passive carbon pool (C_{PSV}–pool), total organic carbon (TOC), available soil phosphorus (Av_P), soil urease activity (SUA), alkaline phosphatase activity, acid phosphatase activity, fluorescein di-acetate activity (FDA), β-galactosidase (β-GaA), *Azotobacter* population, *Azospirillum* population, fungal population, soil microbial biomass carbon (SMBC) and available manganese (Av_Mn) were qualified. In PC2; silt percent and available zinc (Av_Zn) were qualified. Available Fe and soil pH were qualified in PC3. In PC4; available soil potassium; in PC5; available soil nitrogen; in PC6; EC and PC7; soil C: N and CEC were qualified. The least factor loading value (0.46) was observed under PC6; EC, over all other factor loadings in respective PCs, and was selected based on its highest score in comparison with others in PC6 (Table 6). Higher factor loadings ranged from 0.89 to 0.99 under PC1 compared to other data variables in respective PCs.

Soil Properties	Depth (cm)	Tillage (Main plots)			Weed Management (Subplots)			
		T_1: CT(C)-CT(M)-Fallow (N*Sr*)	T_2: CT(C)-ZT(M)-ZT(*Sr*)	T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	W_1- Chemical weed control	W_2- Herbicide rotation	W_3- IWM	W_4- Single hand-weeded control
Physical properties								
Sand (%)	0-15 cm	65.53^{a}	64.93^{a}	64.80^{a}	65.24^{a}	64.99^{a}	64.92^{a}	65.21^{a}
Silt (%)	0-15 cm	12.75^{a}	12.60^{a}	12.69^{a}	12.52^{a}	12.70^{a}	12.77^{a}	12.73^{a}
Clay (%)	0-15 cm	21.73^{a}	22.47^{a}	22.51^{a}	22.25^{a}	22.32^{a}	22.31^{a}	22.06^{a}
BD (Mg m−3)	0-15 cm	1.31^{a}	1.27^{ab}	1.23^{b}	1.28^{a}	1.28^{a}	1.25^{a}	1.27^{a}
BD (Mg m−3)	15-30 cm	1.38^{a}	1.32^{ab}	1.29^{b}	1.35^{a}	1.34^{a}	1.31^{a}	1.32^{a}
MWD (mm)	0-15 cm	0.86^{c}	1.01^{b}	1.38^{a}	1.09^{a}	1.02^{a}	1.03^{a}	1.05^{a}
SPR (MPa)	0-15 cm	1.12^{b}	1.45^{ab}	1.50^{a}	1.30^{a}	1.47^{a}	1.25^{a}	1.45^{a}
SPR (MPa)	15-30 cm	1.69^{ab}	1.73^{a}	1.45^{b}	1.79^{a}	1.50^{ab}	1.55^{ab}	1.66^{ab}
MWHC (%)	0-15 cm	44.02^{b}	46.19^{ab}	47.83^{a}	45.83^{a}	45.47^{a}	45.92^{a}	46.83^{a}
SHC (cm hr−1)	0-15 cm	1.40^{b}	1.45^{ab}	1.59^{a}	1.50^{a}	1.45^{a}	1.50^{a}	1.47^{a}
IR (cm hr−1)	0-15 cm	1.29^{b}	1.36^{ab}	1.41^{a}	1.34^{a}	1.35^{a}	1.38^{a}	1.35^{a}
Physico-chemical and chemical/ fertility properties								
SOC (g kg−1)	0-15 cm	6.71^{b}	7.21^{ab}	7.92^{a}	7.17^{a}	7.22^{a}	7.14^{a}	7.59^{a}
pH	0-15 cm	7.15^{a}	7.14^{a}	7.04^{a}	7.11^{a}	7.09^{a}	7. 13^{a}	7.11^{a}
EC (dS m−1)	0-15 cm	0.45^{a}	0.42^{a}	0.41^{a}	0.42^{a}	0.42^{a}	0.45^{a}	0.41^{a}
CEC (c mol (p +) kg−1)	0-15 cm	19.73^{a}	20.04^{a}	20.05^{a}	20.02^{a}	19.57^{a}	20.04^{a}	20.09^{a}
Avail_N (kg ha−1)	0-15 cm	201.73^{bc}	213.47^{b}	237.70^{a}	216.13^{a}	216.69^{a}	219.01^{a}	217.37^{a}
Avail_P (kg ha−1)	0-15 cm	44.13^{bc}	48.39^{b}	54.98^{a}	48.46^{a}	50.19^{a}	49.86^{a}	48.16^{a}
Continued								

Because of observed significant correlation of soil organic carbon (SOC) with the variables under PC1 with high factor loadings, SOC was solely selected as the indicator from these high positive factor loading characteristics of PC1 to abstain from redundancy. The higher weightage value (0.66) was also observed in PC1 (Table 6).

The significance of SOC as key indicator of soil quality was notable in this current investigation, as announced previously in the literature, for contrastive kinds of farmland practices which encompass conventional agriculture, regenerative agriculture and sustainable agriculture in various agro-ecosystems. The role of SOC is known to alter and bolster many soil functions such as soil microbial and diversity, enzyme activities, bio-geo-cycling of nutrients, soil aggregation, retention and release of soil nutrients etc. Fitly, SOC has been associated and correlated positively with available nutrients, microbial populations, enzyme activities, MWHC, MWD, infiltration rate, active and passive pools of SOC, SPR (15–30 cm), soil C: N, TOC, SMBC and SMBN, SBR, soil pH and EC at 0.05–0.01 significance levels (Panwar et al., 2022; Thakur et al., 2022; Zeraatpisheh et al., 2020). This could be ascribed to improved soil health owing to adoption of conservation agriculture practice. SOC through

Soil Properties	**Depth (cm)**	**Tillage (Main plots)**			**Weed Management (Subplots)**			
		T_1: CT(C)-CT(M)-Fallow (N*Sr*)	**T_2: CT(C)-ZT(M)-ZT(*Sr*)**	**T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS**	**W_1- Chemical weed control**	**W_2- Herbicide rotation**	**W_3- IWM**	**W_4- Single hand-weeded control**
Physico-chemical, chemical and/ or fertility properties								
Avail_K (kg ha−1)	0-15 cm	411.27^{a}	415.24^{a}	429.55^{a}	413.76^{a}	424.37^{a}	429.62^{a}	407.00^{a}
Avail_Mn (kg ha−1)	0-15 cm	5.65^{c}	6.61^{b}	7.76^{a}	6.57^{a}	6.54^{a}	6.91^{a}	6.67^{a}
Avail_Fe (kg ha−1)	0-15 cm	12.70^{bc}	12.93^{b}	13.44^{a}	12.95^{ab}	12.68^{ab}	13.58^{a}	12.88^{ab}
Avail_Cu (kg ha−1)	0-15 cm	0.82^{ab}	0.90^{ab}	1.01^{a}	0.90^{a}	0.93^{a}	0.88^{a}	0.94^{a}
Avail_ Zn (kg ha−1)	0-15 cm	1.60^{a}	1.61^{a}	1.68^{a}	1.61^{a}	1.66^{a}	1.55^{a}	1.69^{a}
Soil C: N	0-15 cm	17.99^{c}	19.87^{b}	20.67^{a}	19.55^{a}	19.82^{a}	19.29^{a}	19.37^{a}
TOC (g kg−1)	0-15 cm	9.29^{ab}	9.79^{ab}	10.49^{a}	9.65^{a}	9.74^{a}	9.93^{a}	10.12^{a}
C_{ACT} pool (g kg−1)	0-15 cm	3.48^{bc}	3.69^{b}	4.04^{a}	3.77^{a}	3.78^{a}	3.61^{a}	3.78^{a}
C_{PSV} pool (g kg−1)	0-15 cm	5.81^{c}	6.10^{b}	6.45^{a}	6.07^{a}	6.11^{a}	6.11^{a}	6.19^{a}
Biological properties								
DHA (µg TPF g−1 day−1)	0-15 cm	52.59^{c}	59.05^{b}	66.24^{a}	52.93^{c}	53.35^{c}	63.74^{b}	67.15^{a}
SUA (µg NH_4–N g−1 h−1)	0-15 cm	70.49^{c}	75.07^{b}	83.59^{a}	70.84^{c}	75.20^{c}	78.29^{b}	81.20^{a}
AlPA (µg PNP g−1 h−1)	0-15 cm	235.20^{c}	277.30^{b}	329.23^{a}	262.61^{c}	268.00^{c}	284.67^{b}	307.03^{a}
AcPA (µg PNP g−1 h−1)	0-15 cm	126.51^{c}	156.20^{b}	164.82^{a}	144.72^{c}	142.97^{c}	151.75^{b}	157.27^{a}
β-GaA (nmol *p* nitrophenol.g^{-1} soil.hr^{-1})	0-15 cm	167.30^{c}	207.59^{b}	249.25^{a}	196.36^{c}	201.33^{c}	213.17^{b}	225.03^{a}
FDA (µg. fluorescein. g^{-1} soil.3h^{-1})	0-15 cm	174.87^{c}	215.30^{b}	273.12^{a}	196.63^{c}	207.07^{c}	237.03^{b}	243.66^{a}
Fungi (×103) CFU g^{-1} soil	0-15 cm	26.20^{c}	33.70^{b}	43.40^{a}	31.30^{c}	32.50^{c}	34.60^{b}	39.30^{a}
Azot (×104) CFU g^{-1} soil	0-15 cm	82.00^{c}	86.90^{b}	101.20^{a}	81.40^{c}	86.50^{bc}	92.50^{b}	102.20^{a}

soil microbial biomass carbon (SMBC) is deemed as one of the most sensitive indicators of changes in soil quality (Stenberg, 1999). Garcia-Gil et al. (2000) also observed that highest SMBC values were pronounced in the most productive soils. SMBC is associated with soil organic matter concentrations (Chaer et al., 2009). Thus, soil SMBC through SOC may also be an accurate indicator for assessing soil quality (Choudhary *et al.*, 2018b).

In dataset, DHA did not appear in variables selected for SQI *i.e.*, it dropped-off from PCA, hence it was not taken further for SQI computation. DHA is highly interlinked with SMBC and that might be the reason for its drop-off as to avoid redundancy. Similar results were reported by Choudhary et al. (2018a). Soil pH has significant impact on soil bio-geochemical processes in the soil and is the “chief soil variable” which influences countless soil properties and processes in occurring in the soil which affect plant development and biomass yield (Neina, 2019).

Soil Properties	Depth (cm)	Tillage (Main plots)			Weed Management (Subplots)			
		T_1: CT(C)-CT(M)-Fallow (N*Sr*)	T_2: CT(C)-ZT(M)-ZT(*Sr*)	T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	W_1- Chemical weed control	W_2- Herbicide rotation	W_3- IWM	W_4- Single hand-weeded control
Biological properties								
Azosp (×104) CFU g^{-1} soil	0-15 cm	67.20^{c}	76.50^{b}	88.80^{a}	72.10^{c}	75.90^{bc}	78.90^{b}	83.10^{a}
SMBC (mg kg−1)	0-15 cm	256.32^{c}	311.24^{b}	349.40^{a}	271.52^{c}	288.64^{bc}	323.68^{b}	337.44^{a}
SMBN (mg kg−1)	0-15 cm	7.91^{b}	9.23^{ab}	9.77^{a}	8.52^{c}	8.41^{c}	9.29^{ab}	9.66^{a}
SBR (mg CO_2. kg^{-1} soil hr^{-1})	0-15 cm	7.72^{b}	8.34^{ab}	8.50^{a}	8.12^{bc}	7.75^{c}	8.25^{ab}	8.58^{a}

Application of crop residues and their retention in the soil and the pieces of roots left-out in soil for years, resulted in a significant reduction in soil pH of 0.2 unit relative to control (no residues addition). Similarly, a reduction of 0.2 units was notable in high pH rice grown soil to which *Sesbania* aculeate was retained (Swarup, 1987) which could be ascribed to the reaction of organic acids and carbon-dioxide emitted from the rhizosphere of *Sesbania* and decomposed organic matter (OM). Similar results were observed in this present experiment in which the pH was numerically reduced where crop residues are retained (ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS).

Available Fe was qualified in the MDS as its shortage is a primary limiting factor which affect crop productivity and soil quality. P availability was also included because the addition of crop residues under ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS increases solubility due to high quantity of organic acids, population of bacteria and enzyme activities particularly alkaline phosphatase (Touhami et al., 2020). Available Zn was retained in the MDS due to its requirement for plant metabolism, enzyme functioning and ion transportation. Thus, inadequate Zn could result in significant loss in production as well as grain content. Similarly, Mn plays a key role in the photosynthesis process and it is predominant in sandy organic soils with pH more than 6.0 (Swarup, 1987), hence it was it included in MDS. The inclusion of silt in MDS could be attributed to its significance in retaining water and circulating air in the soil, thus creating conducive soil environment for the plant growth and soil microorganisms.

Table 5
Calculated eigen values (more than 1), variance percent, cumulative variance percent and weighted values from PCA.

PC	Eigen values	Variance percent	Cumulative variance Percent	Weighted values
1	24.71	63.37	63.37	0.66
2	3.57	9.15	72.52	0.10
3	2.96	7.60	80.11	0.08
4	1.94	4.97	85.09	0.05
5	1.74	4.47	89.56	0.05
6	1.24	3.18	92.74	0.03
7	1.18	3.02	95.76	0.03

Table 6

Variable selection from calculated PCA (+/- of 10%), scoring and factor loadings for calculation of soil quality index as influenced by tillage practices and weed management options during and after harvest of winter maize in the 5th cycle (2022-23).

S.NO	Principal Component (PC)	Column	Variable	Column_ For_ Scoring	Factor loading
1	PC2	2	Silt	2	0.85
2	PC1	1	MWD	3	0.95
3	PC1	1	SPR_2	4	0.94
4	PC1	1	IR	5	0.96
5	PC3	3	pH	6	0.71
6	PC6	6	EC	7	0.46
7	PC7	7	CEC	8	0.54
8	PC1	1	OC	9	0.98
9	PC1	1	C_{ACT-}pool	10	0.97
10	PC1	1	C_{PSV-}pool	11	0.99
11	PC1	1	TOC	12	0.99

Continued.

S.NO	Principal Component (PC)	Column	Variable	Column_ For_ Scoring	Factor loading
12	PC5	5	Av_N	13	0.61
13	PC1	1	Av_P	14	0.89
14	PC4	4	Av_K	15	0.69
15	PC1	1	SUA	16	0.91
16	PC1	1	AlPA	17	0.97
17	PC1	1	AcPA	18	0.93
18	PC1	1	FDA	19	0.98
19	PC1	1	β-GaA	20	0.99
20	PC1	1	*Azot*_pop	21	0.97
21	PC1	1	*Azosp*_pop	22	0.96
22	PC1	1	Fungi_pop	23	0.97
23	PC1	1	SMBC	24	0.92
24	PC7	7	Soil C: N	25	0.52
25	PC3	3	Av_Fe	29	0.68
26	PC1	1	Av_Mn	31	0.93
27	PC2	2	Av_Zn	32	0.82

SPR_2 = soil penetration resistance (15–30 cm), MWD = mean weight diameter, IR = infiltration rate, EC = electrical conductivity, CEC = cation exchange capacity, OC = organic carbon, Soil C: N = soil carbon to nitrogen ratio, Av_N = available soil nitrogen, Av_P = available soil phosphorus, Av_K = available soil potassium, Av_Mn = available soil manganese, Av_Fe = available soil iron, Av_ Zn = available soil Zn, C_{ACT} pool = active carbon pool, C_{PSV} pool = passive carbon pool, TOC = total organic carbon, SUA = soil urease activity, FDA = fluorescein di-acetate activity, AlPA = alkaline phosphatase activity, AcPA = acid phosphatase activity, β-GaA = β-Galactosidase activity, *Azot*_pop = *Azotobacter* population, *Azosp* = *Azospirillum* population, SMBC = soil microbial biomass carbon.

Soil quality index (SQI)

The chosen soil quality indicators were evaluated using homothetic linear transformation, and the SQI was computed through weighted index method on 0 – 1 scale equivalent to 0 – 100%, with the weighting factor calculated using PCA output and scoring in SQI CAL software developed by Mohanty (2020). Soil quality index varied significantly based on treatment combinations (tillage and weed management practices). SQI was significantly higher (62.09%) under ZT + R-ZT + R-ZT + R in combination with single hand-weeded control (T_3W_4), followed by ZT + R-ZT + R-ZT + R on interaction with integrated weed management (T_3W_3) with 59.47% compared to all other treatment combinations (Fig. 3). The lowest SQI (38.75%) was notable under CT-CT-Fallow in combination with chemical weed control (T_1W_1).

Higher SQI observed under ZT + R-ZT + R-ZT + R and single hand-weeded control could be attributed to the higher soil organic carbon (SOC) and associated soil functional parameters (improved microbial population, biomass, enzyme and microbial activities, cycling of the nutrients, hydraulic properties such as infiltration rate, maximum water holding capacity and better soil aggregation compared to conventional tillage (CT) practice with herbicides/ chemicals application and without crop residue addition. This greater SOC content obtained under conservation tillage (ZT + R-ZT + R-ZT + R) farming practice in comparison with conventionally tilled with no input could be ascribed to continuous retention of the crop residues in soil for 3 consecutive years. Aziz et al. (2013) also reported higher SQI under no-till (NT) with crop residues input than in CT systems probably due to more sensitivity of soil microbiological attributes and consistency as soil quality indicators in response to tillage practices. A higher SQI under zero tillage (ZT) was also announced by Mohanty et al. (2007). In this present experiment, the improvement in most of the soil quality indicators resulted in higher SQI values under ZT. Limited soil disturbance in ZT is reported to enhance SOC and soil aggregation etc (Purakayastha et al., 2008).

Soil aggregation is a useful soil health indicator since it is involved in maintaining essential ecosystem functions in soil including organic carbon (OC) accumulation, infiltration capacity, microbial community activity, movement and storage of water and the roots. In addition, it serves as a measure of soil resistance to erosion and management changes (Moebius et al., 2007). Soil CT system which is based on annual ploughing, had an effect on reducing hydro-stability caused by soil compaction and erosion, erosion and degrading soil microorganisms etc. (Cerbari, 2011). Similarly, herbicides/ chemicals applied for weed management in the current experiment, resulted in the significant reduction of all soil biological properties. This could be the reason for lower SQI in treatment combinations which involved the use of herbicides/ chemicals. SQI distribution reached significantly maximal value of 62.09% under ZT + R-ZT + R-ZT + R in combination with single hand-weeded control (T_3W_4) (Fig. 4). The median SQI (49.54%) was under CT-ZT-ZT in combination with integrated weed management (T_2W_3). SQI was significantly distributed at a minimal (38.75%) under CT-CT-Fallow on interaction with chemical weed control. In general, the mean value for SQI was 50.17% (Fig. 4).

System Yield in terms of cotton equivalent yield

The maize yield (Table supplementary 5a) recorded from different tillage – weed management treatment combinations was converted into cotton equivalent yield (CEY) considering the monitory equivalence. Then CEY was subsequently added to the monsoon cotton yield (Table supplementary 5a) of the 3rd year to arrive at the cotton equivalent yield of the cotton – maize system (system CEY) (Table 6) after 3 years. The ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS exhibited a significantly greater CEY (3775 kg ha^{-1}) than CT(C)-ZT(M)-ZT(*Sr*) and CT(C)-CT(M)-Fallow (N*Sr*), with a CEY of 3517 kg ha^{-1} and 3328 kg ha^{-1}, respectively (Table 7). In the current experiment, System CEY demonstrated higher values when subjected to the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS treatment in comparison with other tillage systems. This superior performance can be linked to the development of robust, deep-rooted systems in the crops facilitated by the practice of zero tillage. The adoption of zero tillage is thought to augment the nutrient absorption capacity of the crops, thereby fostering their physiological growth and overall development. Further, the preservation of crop residues on the soil surface under the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS likely contributed to the enhanced retention and availability of soil moisture.

Among the weed management strategies, IWM had a significantly greater system CEY (4157 kg ha^{-1}) than herbicide rotation, chemical weed control and single hand-weeded control with system CEY of 4065 kg ha^{-1}, 4018 kg ha^{-1} and 1921 kg ha^{-1}, respectively (Table 6). Based on the tillage and weed management interaction effects, ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with the IWM, had a significantly greater CEY (4453 kg ha^{-1}), and the lowest CEY values (1767 kg ha^{-1} and 1848 kg ha^{-1}) were observed with CT(C)-ZT(M)-ZT(Sr) in combination with single hand-weeded control and CT(C)-CT(M)-Fallow(N*Sr*) in combination with single hand-weeded control, respectively (Table supplementary 5b). The combination of CT(C)-CT(M)-Fallow (N*Sr*) with all weed management options was also associated with a lower system CEY (Table supplementary 5).

Table 6. System yield in terms of system cotton equivalent yield (CEY) as influenced by tillage practices and weed management options after 3rd year under conservation agriculture.

Treatment	**System (CEY) (kg ha^{-1})**
Tillage practices	
T$_1$: CT(C)-CT(M)-Fallow (N*Sr*)	3328^c
T$_2$: CT(C)-ZT(M)-ZT(*Sr*)	3517^b
T$_3$: ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS	3775^a
Weed Management options	
W$_1$- Chemical weed control	4018^{ab}
W$_2$- Herbicide rotation	4065^{ab}
W$_3$- IWM	4157^a
W$_4$- Single hand-weeded control	1921^c

T$_1$ = conventional tillage (cotton) – conventional tillage (maize) – Fallow (No *Sesbania rostrata*), T$_2$ = conventional tillage (cotton) – zero tillage (maize) – zero tillage (*Sesbania rostrata*), T$_3$= zero tillage (cotton) + *Sesbania rostrata* residues (*Sr*R) – zero tillage (maize) + cotton residues (CR) – zero tillage (*Sesbania rostrata*) + maize stubbles (MS), IWM= integrated weed management. Means within a column in main plots and sub plots with different letters are significantly different at 5% probability level (Duncan multiple rank test). The highest and lowest letter represents the highest and lowest mean, respectively.

Relationship of soil quality index (SQI) and system cotton equivalent yield (CEY) as influenced by tillage practices and weed management option combinations.

The system CEY and SQI were used to evaluate and identify a remunerative tillage – weed management combination with relatively higher SQI and system CEY. This data is presented in Fig. 5. The ZT + R-ZT + R-ZT + R in combination with single hand-weeded control (T$_3$W$_4$), followed by ZT + R-ZT + R-ZT + R and integrated weed management (IWM) treatment combination was observed with the highest SQI. However, the crop productivity of the ZT + R-ZT + R-ZT + R and single hand-weeded control treatment combination was significantly lower compared to all other treatment combinations. Conventional tillage (CT) in combination with all weed management options adopted in this present study recorded lower SQI, but the crop productivity was higher compared to ZT + R-ZT + R-ZT + R in combination with single hand-weeded control (T$_3$W$_4$), which indicate higher productivity but poor soil health. System yield in terms of cotton equivalent yield was higher under ZT + R-ZT + R-ZT + R in combination with IWM which indicated that adoption of cotton with conservation tillage – maize with conservation tillage in combination with IWM practices is a viable strategy to follow for maintenance of both the soil health (good SQI) and good productivity. So, adopting zero tillage with the retention of crop residues in conservation agriculture along with IWM aids towards improving the soil health and optimising crop productivity to the farmer in cotton-maize-green manure cropping system.

Conclusion

On the basis of impact of different tillage practices and weed management options in conservation agriculture (CA) on soil quality and system cotton equivalent (CEY) it is evident that adoption of conservation tillage *i.e.*, ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with single hand-weeded control, followed by integrated weed management (IWM) has significantly enhanced the soil properties and ultimately the soil quality. Among all the soil properties, soil organic carbon (SOC) is the key soil attribute affecting the soil quality in the semi -arid zone of southern India. The system CEY was significantly higher (4453 kg ha^{-1}) under ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS (main plot) and IWM (sub plots). Even though the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with single hand-weeded control has responded positively on enhancing the soil quality, crop productivity was very poor. In view of these, it can be deduced that adopting ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with IWM in CA is a sustainable agricultural practice for improving both the soil quality and optimising system yield under cotton-maize-*Sesbania rostrata* cropping system in the semi-arid regions of southern India. It is also observed that these current findings are the results of three years of CA, which can further be improved with increase in the number of years of this CA trial. Thus, continuous adoption of zero tillage and crop residue retention and IWM in CA practices has got the potential to enhance and maintain soil and agro-ecology, and agro-ecosystem resilience while improving the soil quality and crop productivity. This information garnered in this present investigation is very crucial to the soil scientists, agronomists, farmers and policy makers to deeply understand the development of soil quality and associated agro-ecosystem services.

Declarations

Data Availability and Materials: Author(s) declare that original research data is provided within the manuscript, supplementary materials and the corresponding author can be contacted upon request of data from this study.

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Figures

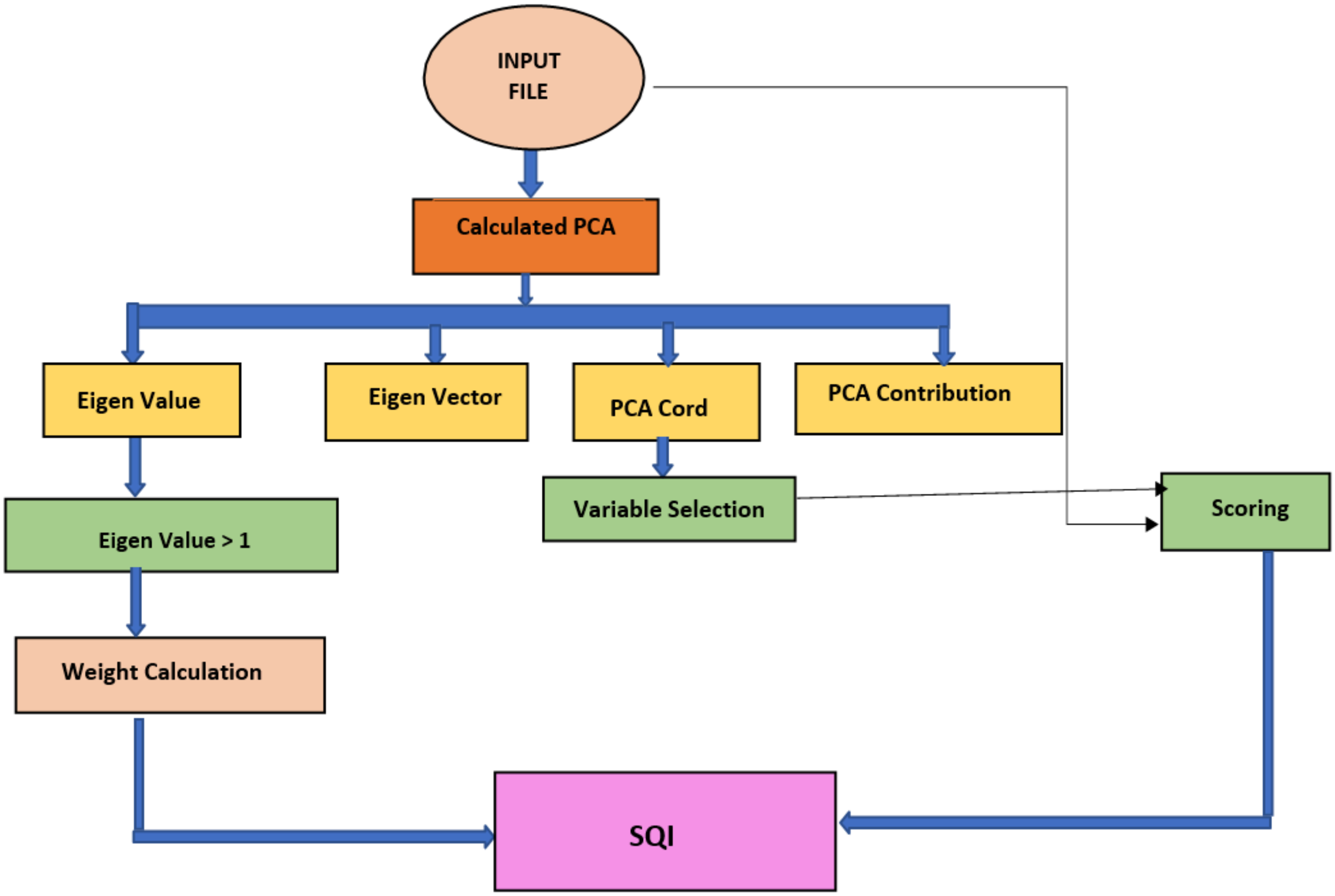

Figure 1

Flow chart of soil quality index computation by SQI CAL software (Mohanty, 2020).

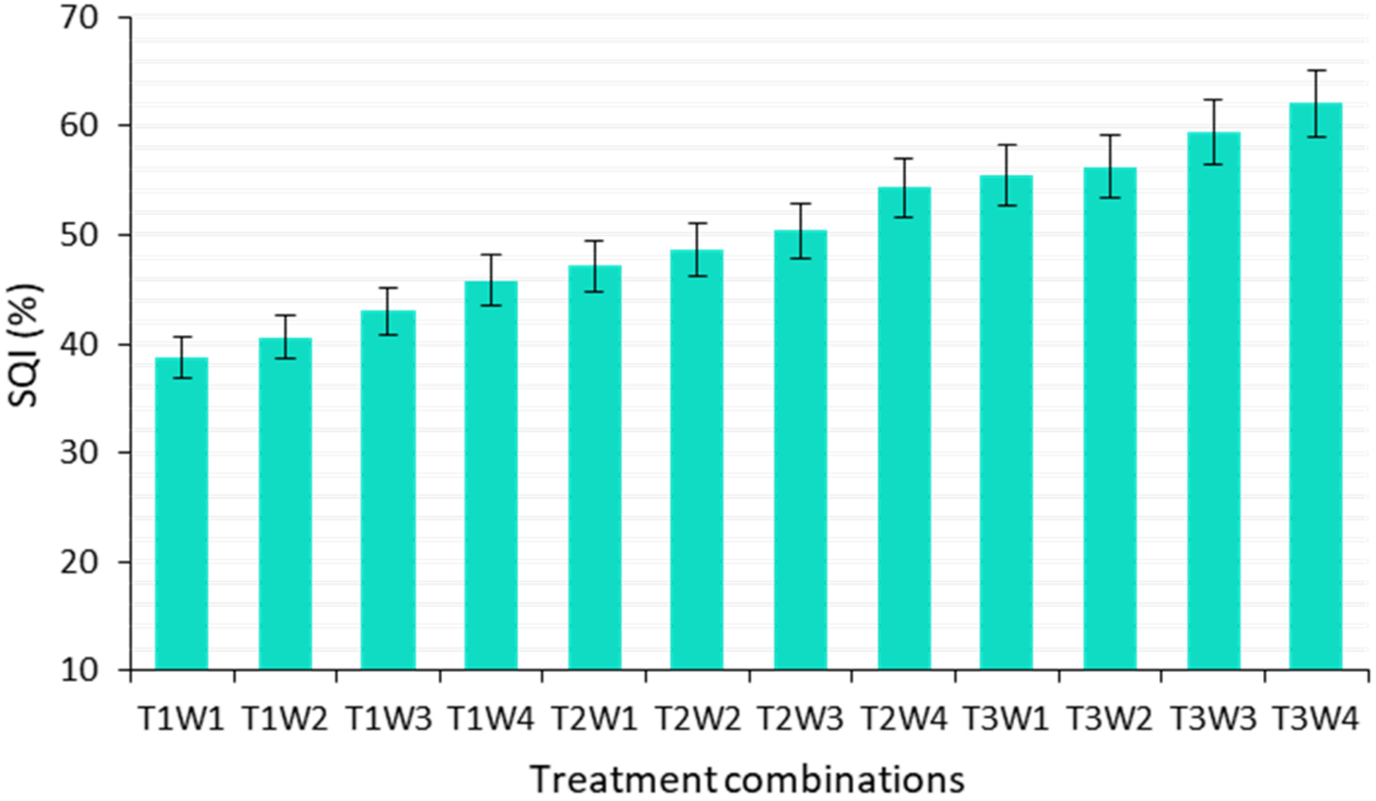

Figure 2

Figure 3: Effect of tillage practices and weed management options on soil quality index (SQI) during and after harvest of winter maize in 2022-23.

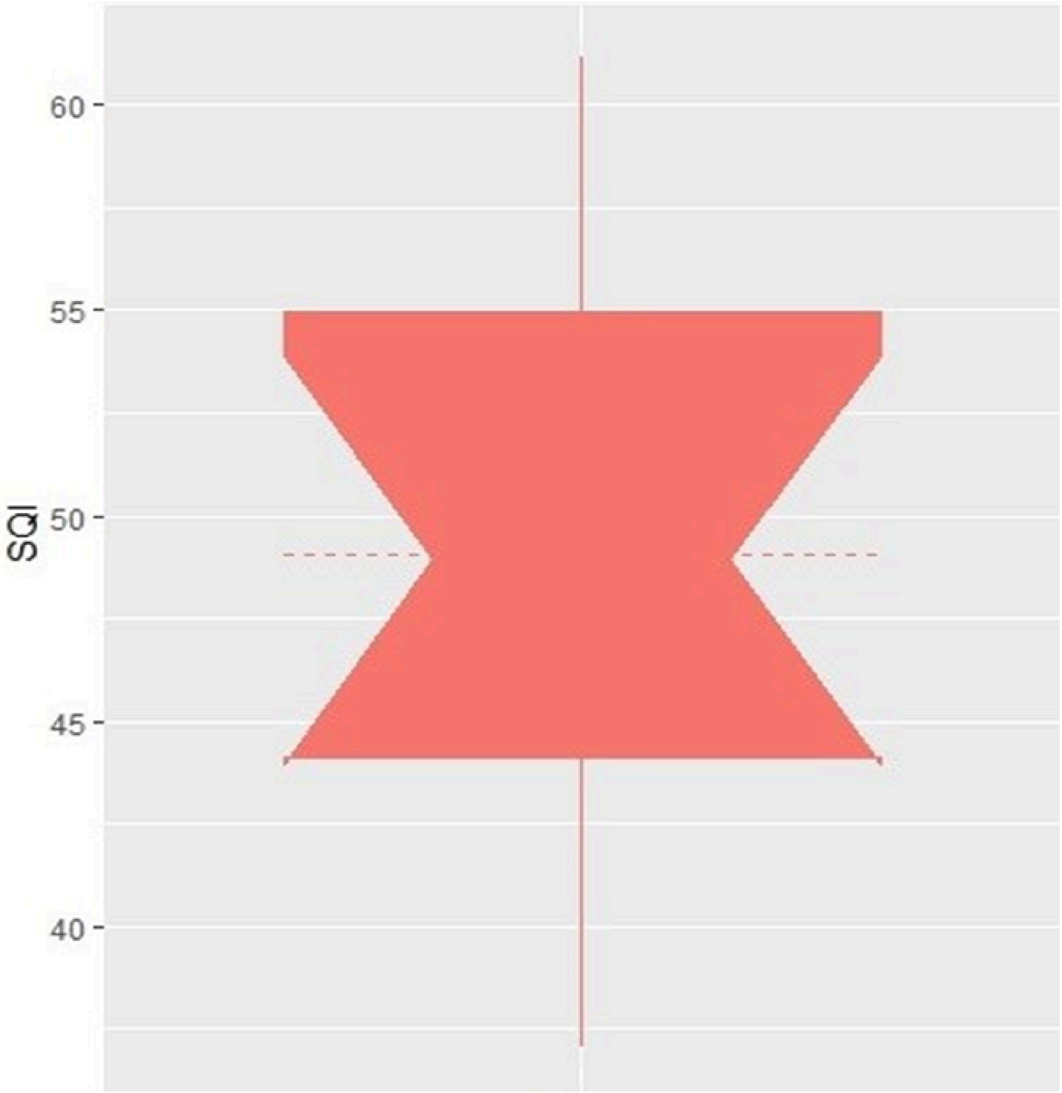

Figure 3

Figure 4: Box plot showing the distribution of SQI (%) as influenced by tillage practices and weed management options during and after harvest of winter maize in 2022-23.

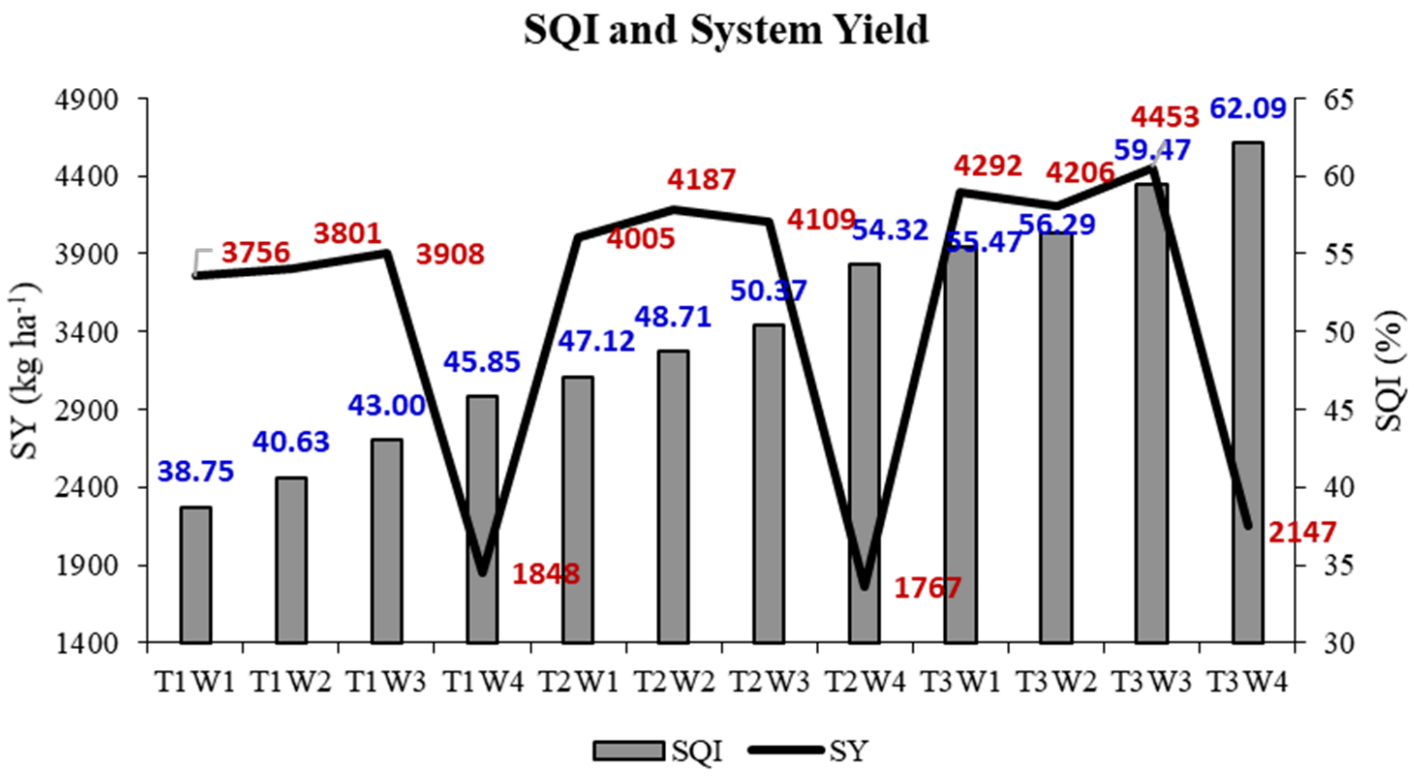

Figure 4

Figure 5: Relationship between soil quality index (SQI) and system yield (SY) in terms of cotton equivalent yield (CEY) in tillage and weed management treatment combinations (2021 and 2022). **Main treatments:** T_1 = conventional tillage (cotton) – conventional tillage (maize) – Fallow (No *Sesbania rostrata*), T_2 = conventional tillage (cotton) – zero tillage (maize) – zero tillage (*Sesbania rostrata*), T_3= zero tillage (cotton) + *Sesbania rostrata* residues (*Sr*R) – zero tillage (maize) + cotton residues (CR) – zero tillage (*Sesbania rostrata*) + maize stubbles (MS); **Sub treatments:** W_1 = Chemical weed control; W_2 = Herbicide rotation; W_3 = Integrated Weed Management; W_4 = single hand-weeded control; CT= Conventional Tillage, ZT= Zero Tillage.

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