sustainability

MDPI

Article

Impact of Conservation Agriculture on Soil Quality and Cotton–Maize System Yield in Semi-Arid India

Knight Nthebere [1,*], RamPrakash Tata [1], Padmaja Bhimireddy [1], Latha P. Chandran [2], Jayasree Gudapati [1], Meena Admala [1], Nishant K. Sinha [3], Thumma B. Srikanth [1,2] and Kavuru Prasad [2]

1 Department of Soil Science and Agricultural Chemistry, Jayashankar Telangana State Agricultural University, Hyderabad 500030, India; trp.soil@gmail.com (R.T.); bhimireddymaduri@gmail.com (P.B.); gjayasree2001@yahoo.com (J.G.); meenaadmala22@gmail.com (M.A.); srikanthreddythumma2@gmail.com (T.B.S.)

2 Indian Council of Agricultural Research-Indian Institute of Rice Research (ICAR-IIRR), Indian Institute of Rice Research, Hyderabad 500030, India; lathapc@gmail.com (L.P.C.); kavurussm@gmail.com (K.P.)

3 Indian Council of Agricultural Research-Indian Institute of Soil Science (ICAR-IISS), Indian Institute of Soil Science, Madhya Pradesh, Bhopal 462038, India; nishant.sinha76211@gmail.com

* Correspondence: knthebere@gmail.com

Abstract: Intensive agriculture is the chief cause of soil degradation, particularly in regions with low soil organic carbon status, such as semi-arid southern India. In the quest to attain sustainable yield and improved soil quality, conservation agriculture (CA) is being advocated and adopted globally, including in India. In this experiment, CA was implemented to investigate the synergistic impacts of tillage and weed management on soil quality index and system yield and to identify a remunerative treatment combination that can sustain system yield and enhance soil quality. Contrasting tillage practices (main plots) included the T_1: conventional tillage with cotton–conventional tillage with maize–fallow, i.e., no *Sesbania rostrata* (Farmers' practice), T_2: conventional tillage with cotton–zero tillage with maize–zero tillage with *Sesbania rostrata* and T_3: zero tillage with cotton + *Sesbania rostrata* residues–zero tillage with maize + cotton residues–zero tillage with *Sesbania rostrata* + maize stubbles. Weed management tactics (sub-plots) were W_1: chemical weed control, W_2: herbicide rotation, W_3: integrated weed management and W_4: single hand-weeded control in a split-plot design with cotton–maize–*Sesbania* cropping system over 3 years, in a split-plot design. Principal component analysis (PCA) was performed using the soil quality index (SQI)-CAL Version 1.0 software tool to extract minimum datasets from measured soil properties. A total of 40 soil variables were analyzed at 60 DAS and after the maize harvest, then subjected to principal component analysis (PCA) and subjected to PCA in soil quality index (SQI)-CAL software as to choose variables, minimum dataset and obtain soil quality index. The following soil properties, soil organic carbon (SOC), silt fraction, available soil zinc (Zn), iron (Fe), potassium (K), nitrogen (N), pH, electrical conductivity (EC), soil carbon to nitrogen (C:N) and cation exchange capacity (CEC), were selected as indicators based on correlations, calculated PCA and adept opinions on texture and lime concretions of experimental soil. The soil quality index improved by 23.34% in the T_3W_4 compared to T_1W_1. The system yield was 51.79% higher with the adoption of T_3W_3 compared to T_3W_4 combinations. Therefore, considering both system yield and soil quality index, T_3 and W_3 were remunerative and the best treatment combination among all others to sustain both soil and crop productivity in this region.

Keywords: soil quality; crop productivity; conservation agriculture; sustainability; cropping system

check for updates

Academic Editor: Teodor Rusu

Received: 6 December 2024
Revised: 17 January 2025
Accepted: 18 January 2025
Published: 25 January 2025

Citation: Nthebere, K.; Tata, R.; Bhimireddy, P.; Chandran, L.P.; Gudapati, J.; Admala, M.; Sinha, N.K.; Srikanth, T.B.; Prasad, K. Impact of Conservation Agriculture on Soil Quality and Cotton–Maize System Yield in Semi-Arid India. *Sustainability* **2025**, *17*, 978. https://doi.org/10.3390/su17030978

1. Introduction

Soil, the dynamic living soul, contributes value to humans; however, its potential benefits may be hindered by threats unless properly managed. This soil is degrading rapidly due to the intensive use of tillage operations, shrinking away precious natural resources available for crop production and other agri-related endeavors [1]. Such improper agricultural practices result in the loss of not only soil productivity but also a decrement in soil's capacity to perform its ecological functions and ecosystem services, which ultimately leads to the reduction in soil quality (SQ). Another challenge is the alarming rate of population increase, which would make it impossible to feed about 9.7 billion people by 2050 worldwide [2,3]. Since the 1970s, India has been suffering from the demand for food production due to a surge in population [4–6].

In 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, including India and its semi-arid zones [7], to sustain soil resources and crop productivity. CA has been gaining momentum worldwide, with a total area of 205 M ha globally in 2022 and 3.5 M ha in India during 2018–2019 [8,9]. It is defined as "a concept for resource-saving agricultural crop production levels while concurrently conserving the environment" [10]. FAO presents the slogan of "Healthy soils for healthy life" during "International Year of Soils-2015" and puts emphasis on soil sustainable management, which can be possible only by knowing the health of the soil through assessment of its quality (http://www.fao.org/soils-portal/en/ accessed on 5 December 2015). In this context, CA is being promoted in India through the National Mission for Sustainable Agriculture (NMSA) (Pradhan Mantri Krishi Synchayee Yojana-PMKSY). However, in conditions not well adapted for conservation agriculture (CA) implementation, considering agronomic and agro-ecological complications, CA may be unsuitable [7,11].

It may be noted that among other practices within CA, weed control is often achieved through the adoption of the latest development: pre- and post-emergence broad-spectrum herbicides due to shortage of labor for weeding, thus maintaining the crop stand and yield same as in conventional production system [12]. 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 the soil as a result of various agricultural management practices, such as tillage and weed control strategies being implemented, can be assessed through the evaluation of different physico-chemical, chemical, physical and biological soil properties [13]. These soil characteristics aid in the qualitative assessment of SQ depending on separate variables. Nevertheless, to contrast the effect of specified agricultural production systems on soil, a quantitative index must be used to formulate an assessment thoroughly and deduce whether they are good, poor or moderate [14]. Such an index aids in grouping the impacts of cropping practices holistically and evaluating the development or degeneration interlinked with soil functions at both local and regional scales. Similarly, to evaluate SQ in each homogeneous soil type with the 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 [14].

A quantitative evaluation technique is the soil quality index (SQI), which is an optimal logic method to find out whether SQ values rise, stay the same or decline under contrastive cropping practices [15]. Several studies conducted across the globe and in India have reported that the 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 [16–19]. 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 the global level and in India, there is scanty information on the synergistic 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. Combining contrasting tillage practices and weed management options could benefit the farmers in identifying sustainable tillage practices coupled with weed control practices for implementation in the fields. Thus, this current investigation has been implemented to identify remunerative tillage and weed management combinations for sustaining crop productivity and improving the SQ and to assess the synergistic 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.

2. Material and Methods

2.1. 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°18′17″ N latitude and 78°25′38″ E longitude. The satellite outlook of the field is presented in Supplementary Figure S1. The field experiment was implemented from 2020 to 2021 in the monsoon, winter and summer seasons under cotton (*Gossypium hirsutum*), maize (*Zea mays*) and green manure (*Sesbania rostrata*) rotations, respectively. The cotton (sadanand), maize (DHM 117) and *Sesbania rostrata* seed varieties (plant seeds) used in the present study were developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, and the use of these plant seeds in the current experiment complies with the international, national and/or institutional guidelines. Cotton is photo-thermo sensitive, maize is thermo sensitive, and *Sesbania rostrate* is a legume cover crop. Hence, these crops were selected as the research objects in the monsoon, winter and summer seasons, respectively, in accordance with the principles of conservation agriculture (CA) under semi-arid conditions of the Southern Telangana region. The experiment continued from 2020–2021 to 2022–2023 without disturbing the field layout at the same site. The monthly Meteorological observations taken on a weekly basis during the crop development from the station situated at the Institute of Agricultural Research (IAR), Rajendranagar, are presented in Supplementary Figures S2 and S3.

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., iron (Fe), manganese (Mn), zinc (Zn) and copper (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 were 43.80%, 0.79 mm, 1.22 cm h^{-1} and 1.28 cm h^{-1}, respectively.

2.2. Design of the Experiment and Treatment Details

A conservation agriculture (CA) experiment was conducted using a split-plot design. The design (split-plot) is essential for tillage and weed management practices because it allows the effects of each variable (tillage and weed management practices) on those examined (yield, soil properties and soil quality index) to be isolated. This could benefit the farmers and researchers who are determining the effective tillage and weed control practices in Southern Telangana State. The three contrasting tillage practices in the main plots are as shown in Table 1; the four weed management options in the sub-plots are 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 plowing two times, followed by rotovating and seeding. In T_2, no-till of the soil (zero tillage, ZT), i.e., seeding was performed 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 and 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 rostrata* retained in T_3 plots since the year 2020–2023 was about 200.0 to 240.0 Mg ha^{-1}, estimated according to [20]. 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 the sowing of summer *Sesbania rostrata*, as it was cultivated for 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. These practices are experimental in the semi-arid regions of Southern Telangana State and need to be widely used in future research.

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 tillage (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 T_2 T_3	Diuron pre-emergence (PE) application 0.75 kg/ha *fb* tank mix application 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 performed after the critical period of crop-weed competition, i.e., between 45 and 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 120 g/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 120 g/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* halo-sulfuron methyl 67.5 g/ha at 20–25 DAS as PoE (T_1).	Tembotrione 120·g/ha and Atrazine 50% WP 0.5 kg/haboth applied as early post-emergence) EPoE *fb* brush cutter at 40 DAS.	One hand-weeding was performed after the critical period of crop-weed competition, i.e., between 45 and 50 days after sowing).

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.

3. Crop Management Practices

3.1. Sowing and Fertilizer Application

The experimental particulars and characteristics of cotton, maize and *Sesbania* cultivars used are presented in Supplementary Tables S1 and S2, respectively. Prior to the seeding of cotton and maize, the experimental plots were plowed two times, accompanied by rotovating and leveling 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. *Sesbania rostrata* was included in the cropping system as a green manure crop because of its capacity to add nitrogen through the fixation process and organic matter to the soil while reducing fertilizer needs and enhancing soil quality [21–23]. 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. The recommended dose of fertilizers (RDFs) for maize was N-P_2O_5-K_2O (200:60:50 kg ha^{-1}). Urea and DAP in maize were split thrice as basal, at knee height and at tasseling period (60 DAS). No fertilizer was applied 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.

3.2. Soil Analysis

3.2.1. Sampling and Standard Analytical Procedures

Soil Physico-Chemical, Chemical and/or Fertility Properties

Composite soil samples were randomly collected from 36 plots through the collection of 36 surface soil samples (0–15 cm soil depth) in triplicates at different spots in triplicate from each treatment plot established under conservation agriculture at a depth of 0–15 cm and 15–30 cm (based on the parameter under estimation) after harvest of maize crop in the fifth 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 2 mm sieve, labeled and stored in polythene covers to be analyzed for different physical, physico-chemical chemical/fertility properties of the soil by duly following the standard procedures (Supplementary Tables S3 and S4).

3.3. Soil Biological Properties

Rhizosphere samples were collected from 36 plots at the tasseling stage, i.e., 60 days after sowing (DAS) of maize crop (fifth crop cycle) in 2022–2023. These samples, which were taken from each respective plot at different spots in triplicates, were homogenized, kept in polythene bags with zippers to the laboratory, passed through 2 mm sieve and analyzed on the same day as collected from the field for soil microbial population, enzyme activity and microbial activity (Supplementary Table S5) by duly following the standard protocols. The choice for these parameters thereof, among other soil parameters, was made based on their sensitivity and rapid response toward any agricultural management practices. Therefore, they are considered direct indicators of soil quality in agro-ecosystems of the whole world. Soil water content was determined according to [24], and the information was utilized in calculating the evaluated soil biological parameters.

4. Computation of Soil Quality Index (SQI)

The effect of tillage and weed management practices in conservation agriculture (CA) on soil quality was assessed by the weighted index method with SQI CAL software—A Tool for Soil Health Assessment based on principal component analysis (PCA) methodologies [25]. This SQICAL tool (https://nishantsinha51.shinyapps.io/SQICAL/ accessed on 28 October 2020) performed principal component analysis (PCA) for extracting minimum datasets from measured soil properties. The PCA linearly reduces the data dimensionality while limiting the loss of information by creating uncorrelated principal components (PCs). The principal components (PCs) encompass contributions from all soil variables and are arranged such that the first few PCs capture the majority of the variance from the original dataset. The PCs that received high eigenvalues were assumed to best represent the variation in the system. Therefore, only the PCs with eigenvalues >1 were considered in this tool. Under a particular PC, each variable was given a factor loading that represents the variable contribution to the particular PC. Only the variables with high factor loadings were retained from each PC for soil quality indexing. When multiple variables were retained under a single PC, a multivariate correlation analysis was performed to determine the relation among them and could be eliminated from the soil quality index (SQI). If the highly loaded factors were not correlated, then each variable was deemed important and retained in the SQI. Among well-correlated variables, the one with the highest absolute factor loading was selected for inclusion in the SQI. Further, the weights were assigned based on the variance explained by each PC. This variance percentage, standardized to unity, provided the weight for variables chosen under a given PC.

The input data required for the SQI computation were arranged in CSV format and uploaded to SQI CAL software, and principal component analysis was calculated from the input data according to the flow chart presented in Figure 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 analyzed soil properties, variable selection from calculated PCA (+/of 10%) and minimum data set (MDS) were selected to avoid redundancy [6,12]. 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 (Supplementary Table S6) 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 Equation (1), using the updated weight and scoring output as below:

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

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

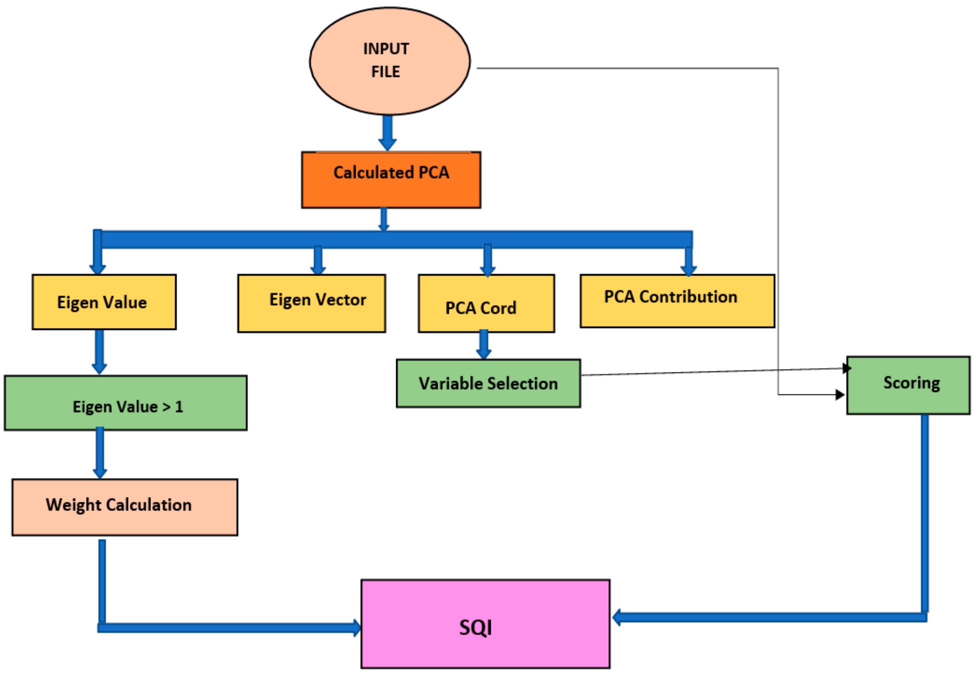

Figure 1. Flow chart of soil quality index computation by SQI CAL software (Mohanty, 2020).

5. Crop Productivity

The yield of seed cotton and maize grain (kernel yield) were recorded after harvest in monsoon (2022) and winter (2022–2023), respectively, and the yield data are provided in Supplementary Table S7. For cotton, the total seed cotton was harvested in three pickings at weekly intervals from each net plot according to the treatments, pooled, weighed separately and expressed in kg ha^{-1}. The sum of seed cotton per plot picked at different pickings, together with the yield of tagged plants and bolls, was taken as seed cotton yield per plot and expressed in kg ha^{-1}. Subsequent to the harvesting of seed cotton, the stalks of cotton from each net plot were 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 Equation (2), as below:

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

6. Statistical Analysis

The data were analyzed statistically by applying the analysis of variance technique, duly following the ANOVA for split-plot design, as suggested by Panse and Sukhatme [26]. Critical difference for examining the treatment means for their significance at a 5% probability level was performed by the 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 performed by using SQICAL software (https://nishantsinha51.shinyapps.io/SQICAL/ accessed on 28 October 2020) provided by Mohanty [27].

7. Results and Discussion

7.1. Soil Physical Attributes

The alterations in soil physical characteristics at the end of the third year (fifth maize crop cycle) were significantly influenced by the adoption of different tillage practices (Table 3). 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 3). Among the tillage practices, the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS was observed with 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 3). 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 plays a key role and are considered the primary binding agents through the release of polysaccharide compounds during the decomposition, which in turn contribute to the formation of macroaggregates and enhanced overall soil physical attributes [28–30]. Boogar et al. [31] and Nthebere et al. [1] also reported positive effects of adopting conservation tillage (minimum or no-till) on the formation of more stable aggregates and improved physical properties.

7.2. 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 the harvest of maize (fifth crop cycle) except soil organic carbon (SOC), which demonstrated a significant change influenced by different tillage practices. This significant change in SOC with the adoption of tillage practices over other soil fertility indicators could be because overall soil nutrients are determinants of SOC as the key element in soil quality [18,32]. The SOC affects the physico-chemical properties of soil, which simultaneously enhances other soil properties [33]. 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 3). Fertility properties of the soil viz., macronutrients (N, P:P_2O_5, K:K_2O) and micronutrients (Mn, Fe, Zn, Cu) were significantly influenced by tillage methods except for available soil K (K_2O), Zn and Cu (Table 3). 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 3). 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 aggregate formation, which in turn yields SOM, hence an increase in soil nutrient availability [34,35]. 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 the high energy demand for microbes. The rate of decomposition of added crop residues influences nutrient cycling (particularly N) and thus impacts the availability of nitrogen to plants. Generally, when residues with a wider C:N are retained in the soil, immobilization of N will occur, in which the succeeding crop will show N deficiency.

7.3. 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 3). 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 (Supplementary Tables S8 and S9). 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, favored by the prevalence of soil microorganisms, likely contributed to this observed enhancement.

7.4. 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 were utilized to calculate the soil quality indices to ascertain the performance of the treatments in maintaining soil quality. A considerable number of 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 correlated at $p = 0.05$ (Supplementary Table S10) among the soil parameters. The details of the soil parameters, which are considered correlated at $r = 0.05$, and the calculated PCA is presented in Table 4.

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 4). 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 5). 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 was qualified; in PC5, available soil nitrogen was qualified; in PC6, EC and PC7, soil C:N and CEC were qualified. The least factor loading value (0.46) was observed under PC6 only EC appeared in the PC 6 and was the least over all other factor loadings in respective PCs and was selected based on its highest score in comparison with others in PC6 (Table 5). Higher factor loadings ranged from 0.89 to 0.99 under PC1 compared to other data variables in respective PCs. Because of the 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 5).

The significance of SOC as a key indicator of soil quality was notable in this current investigation, as announced previously in the literature, for contrastive kinds of farmland practices that 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 [6,36,37]. This could be ascribed to improved soil health owing to the adoption of conservation agriculture practices. SOC through soil microbial biomass carbon (SMBC) is deemed as one of the most sensitive indicators of changes in soil quality [38]. SMBC is associated with soil organic matter concentrations [39]. Thus, soil SMBC through SOC may also be an accurate indicator for assessing soil quality [17]. The significance of SMBC and soil enzyme activities examined in this study being retained in PC 1, demonstrates that restoration in soil quality has been brought by effective tillage practice and weed management, i.e., ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS and single hand-weeded control combinations, respectively, well known to have the potential to unlock sustainability, economical success of marginal soils and stimulate microbial population being measured as SMBC, which in turn enhances enzyme activities [33,40–42].

In the 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 to avoid redundancy. Similar results were reported by Choudhary et al. [17]. Soil pH has a significant impact on soil bio-geochemical processes in the soil and is the "chief soil variable", which influences countless soil properties and processes occurring in the soil, which affect plant development and biomass yield [43]. Application of crop residues and their retention in the soil and the pieces of roots left out in the soil for years resulted in a significant reduction in soil pH of 0.2 units relative to the control (no residue addition). Similarly, a reduction of 0.2 units was notable in high pH rice-grown soil to which *Sesbania* aculeate was retained [44], 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 were 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 that affects 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 [45]. Available soil zinc was retained in the MDS due to its requirement for plant metabolism, enzyme functioning and ion transportation. Thus, inadequate zinc could result in a significant loss in production as well as grain content. Similarly, available soil manganese plays a key role in the photosynthesis process, and it is predominant in sandy organic soils with a pH of more than 6.0 [44]; hence, it was included in the minimum dataset (MDS). The inclusion of silt in MDS could be attributed to its significance in retaining water and circulating air in the soil, thus creating a conducive soil environment for plant growth and soil microorganisms.

Table 3. Impact of tillage practices and weed management options on soil properties during and after harvest of winter maize in the 5th cycle (2022–2023).

Soil Properties	Depth (cm)	Tillage (Main Plots)			Weed Management (Sub-plots)			
		T_1: CT(C) − CT(M) − F allow (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 Her Bicide Rotation	W_3 IWM	W_4 Single H and Weeded Control
Physical properties								
S and (%)	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}
Cl ay (%)	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 (MP a)	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 (MP a)	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 h^{-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 h^{-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}
Av ail_N (kg h a^{-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}
Av ail_P (kg h a^{-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}
Physico-chemical, chemical and/or fertility properties								
Av ail_K (kg h a^{-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}
Av ail_Mn (kg h a^{-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}
Av ail_Fe (kg h a^{-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}
Av ail_Cu (kg h a^{-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}
Av ail_ Zn (kg h a^{-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}

Table 3. *Cont.*

Soil Properties	Depth (cm)	Tillage (Main Plots)			Weed Management (Sub-plots)			
		T_1: CT(C) − CT(M) − F allow (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 Her Bicide Rotation	W_3 IWM	W_4 Single H and Weeded Control
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				
DH A (μg TPF g^{-1} d ay−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}
SU A (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}
AlP A (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}
AcP A (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-G a A (nmol. *p* nitro-phenol.g^{-1} soil.h^{-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}
FD A (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 ($\times 10^3$) 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 ($\times 10^4$) 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}
Azosp ($\times 10^4$) 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}
SM BC (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}
SM BN (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}
S BR (mg CO_2. kg^{-1} soil h^{-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}

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 (SrR)–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. The $^{a, b, c, ab, bc}$ indicates significant differences among the means of the treatments. The means having distinct letters demonstrate significant variances between the treatments at 5% probability level (Duncan multiple rank test) and means having the same letters indicate no significant variances among the treatment means at 5% probability level.

Table 4. 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 5. 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 (2022–2023).

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
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.

7.5. Soil Quality Index (SQI)

The chosen soil quality indicators were evaluated using a homothetic linear transformation, and the SQI was computed through the weighted index method on a 0–1 scale equivalent to 0–100%, with the weighting factor calculated using PCA output and scoring in SQI CAL software developed by Mohanty [27]. 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 (Figure 2). The lowest SQI (38.75%) was notable under CT-CT-Fallow in combination with chemical weed control (T_1W_1).

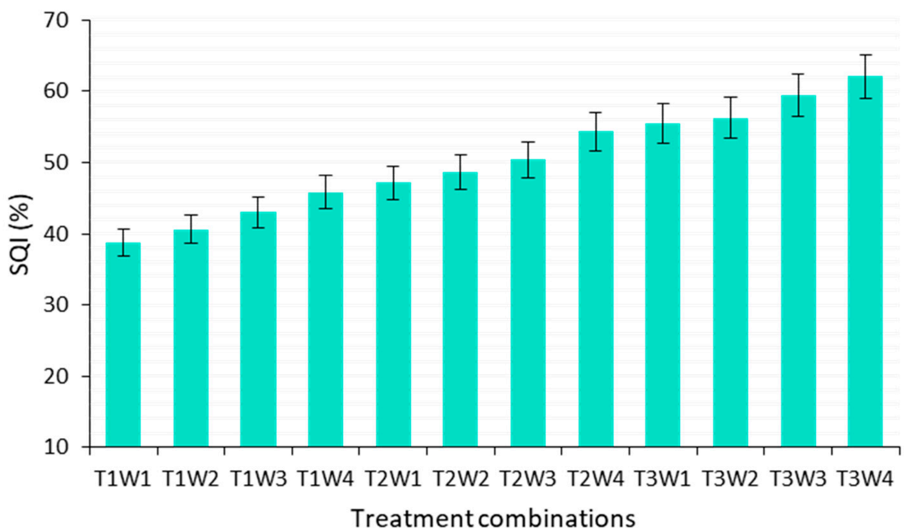

Figure 2. Effect of tillage practices and weed management options on soil quality index (SQI) during and after harvest of winter maize in 2022–2023. The vertical bars represent error bars at a 5% significant level.

Higher SQI (62.09%) observed under ZT + R-ZT + R-ZT + R and single hand-weeded control combination (T_3W_4) could be attributed to reduced soil disturbance, which resulted in soil moisture preservation and increased soil organic carbon (SOC), and associated soil functional parameters (improved microbial population, biomass, enzyme and microbial activities, cycling of the nutrients, hydraulic properties and better soil aggregation) compared to conventional tillage (CT) practice with herbicides/chemicals application and without crop residue addition [46]. Single hand-weeded control is thought to increase soil biodiversity because of biophysical conditions created for survival and the preponderance of microorganisms due to weed management with cultural control practice [46]. This implies sustainable soil management practices for the farmers with the adoption of T_3W_4. However, due to a shortage of laborers to perform manual weeding and low yield with ZT + R-ZT + R-ZT + R and single hand-weeded control combinations, this practice may not be suitable for the farmers to adopt in the Southern Telangana State of India. Higher SQI was also reported by Aziz et al. [16] under no-till (NT) with crop residues input than in conventional tillage (CT) systems, probably due to more sensitivity of soil microbiological attributes and consistency as soil quality indicators respond directly and rapidly to tillage practices. In this present experiment, the improvement in most of the soil quality indicators resulted in higher SQI values under zero tillage (ZT). Limited soil disturbance in ZT was reported to enhance SOC and soil aggregation, etc. [47].

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 [48]. Soil conventional tillage (CT) systems based on annual plowing had an effect on reducing hydro-stability caused by soil compaction and erosion, erosion and degrading soil microorganisms, etc. [49]. Similarly, herbicides/chemicals applied for weed management in the current experiment resulted in a significant reduction in 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 a significantly maximal value of 62.09% under ZT + R-ZT + R-ZT + R in combination with single hand-weeded control (T_3W_4) (Figure 3). The median SQI (49.54%) was under CT-ZT-ZT in combination with integrated weed management (T_2W_3). SQI distribution was minimum (38.75%) under CT-CT-Fallow on interaction with chemical weed control. In general, the mean value for SQI was 50.17% (Figure 3 and Table 6).

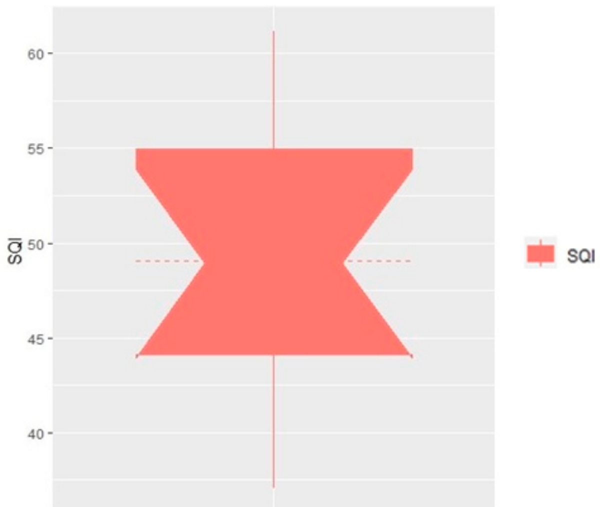

Figure 3. Box plot showing the distribution of soil quality index (SQI) in percentage (%) as influenced by tillage practices and weed management options during and after harvest of winter maize in 2022–2023.

Table 6. Statistical summary of SQI (%) in boxplot.

Descriptive Statistics	SQI
Mean	50.17
Standard Error	2.16
Median	49.54
Kurtosis	−1.08
Skewness	0.03
Minimum	38.75
Maximum	62.09
CV	14.90

7.6. System Yield in Terms of Cotton Equivalent Yield

The maize yield (Supplementary Table S7) 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 (Supplementary Table S5) of the third year to arrive at the cotton equivalent yield of the cotton–maize system (system CEY) (Table 7) 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).

Table 7. Impact of tillage practices and weed management options on system yield in terms of system cotton equivalent yield (CEY) after 3rd year under conservation agriculture.

Treatment Interaction Tillage	WM	System (CEY) (kg ha^{-1})
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	W_1	3756
	W_2	3801
	W_3	3908
	W_4	1848
	W_1	4005
T_2: CT(C)-ZT(M)-ZT(*Sr*)	W_2	4187
	W_3	4109
	W_4	1767
T_3: ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS	W_1	4292
	W_2	4206
	W_3	4453
	W_4	2157
Tillage practices		
T_1: CT(C)-CT(M)-Fallow (N*Sr*)		3328
T_2: CT(C)-ZT(M)-ZT(*Sr*)		3517
T_3: ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS		3775
Weed management options		
W_1 Chemical weed control		4018
W_2 Herbicide rotation		4065
W_3 IWM		4157
W_4 Single hand-weeded control		1921
	SE (m)±	CD (p = 0.05)
Tillage	18.69	73.38
Weed management	40.29	119.71
Interactions		
W at same level as T	69.79	207.35
T at same level as W	63.26	187.96

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 a 5% probability level (Duncan multiple rank test). The highest and lowest letter represents the highest and lowest mean, respectively.

In the current experiment, system cotton equivalent yield (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 7). 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 (Supplementary Table S8). The combination of CT(C)-CT (M)-Fallow (N*Sr*) with all weed management options was also associated with a lower system CEY (Supplementary Table S5).

7.7. Relationship of Soil Quality Index (SQI) and System Cotton Equivalent Yield (CEY) as Influenced by Tillage Practices and Weed Management Option Combinations

The system cotton equivalent yield (CEY) and soil quality index (SQI) were used to evaluate and identify a remunerative tillage–weed management combination with relatively higher SQI and system CEY. These data are presented in Figure 4. The ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with single hand-weeded control (T_3W_4), followed by ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS and integrated weed management (IWM) treatment combination was observed with the highest SQI. However, the crop productivity of the ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS 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(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with single hand-weeded control (T_3W_4), which indicate higher productivity but poor soil health. System yield in terms of cotton equivalent yield was higher under ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS in combination with IWM, which indicated that the adoption of cotton with conservation tillage–maize with conservation tillage in combination with IWM practices is a viable strategy to be followed by the farmers for maintenance of both the soil health (good SQI) and good productivity. This could be the result of the synergistic effects of efficient weed management achieved using cultural and mechanical control tactics, as well as moisture and nutrient preservation facilitated by no-till practices with crop residue retention. So, adopting zero tillage with the retention of crop residues in conservation agriculture along with IWM could aid in improving soil health and optimizing crop productivity for the farmer in a cotton–maize green manure cropping system.

Limitations of the Study and Way Forward

The conservation agriculture (CA) with conservation tillage (ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS) adopted in the experiment has demonstrated a clear soil quality index and system yield gains over conventionally managed systems. In particular, its capability to help cut-off input costs, increase soil organic carbon and subsequently enhance the soil's physical, physico-chemical, fertility and biological properties, and increased crop yields is highly valued [46]. However, implementing CA has significant challenges, and a number of approaches are needed to scale-up its worldwide adoption. Farmers need access to a range of agricultural tools and resources that would allow them to identify whether the CA principles are likely to be appropriate for their operation and successfully overcome some of the challenges that can be associated with its use. One of the major challenges observed not only in the semi-arid regions of Southern Telangana State of India but in other regions of the world on CA is its provision for conducive conditions for perennial weeds in most of the cropping system [50]. Traditionally, farmers in the Southern Telangana region manage the weeds in cereal crops under CAby pre-emergence herbicide application followed by inter-cultivation and manual weeding. Whereas in predominant crops such as cotton, etc., weed management is mostly by inter-cultivation or pre-emergence herbicide application followed by inter-cultivation with cattle-drawn/tractor-drawn implements. The introduction of these new-generation selective herbicides and the shortage of labor for manual weeding have resulted in a significant increase in pre-emergence and post-emergence herbicide use in these crops. Even though weed control through the application of herbicides is widely accepted and effective (Dass et al., 2017) [51], the extensive use of herbicides, i.e., in herbicide-treated plots (W_1—chemical control and W_2—herbicide rotation in alternative years) significantly affected the soil microbial activities, population and enzymes negatively, which reflected on soil processes, particularly soil organic carbon, a key indicator for soil quality. The short duration (three years) of the experiment could also limit the insights into conservation agriculture (CA) in the semi-arid region of India. Therefore, future research should explore and incorporate microbial-derived herbicides along with contrasting tillage practices in CA to monitor their influence on soil biological attributes, soil quality and crop yield. Studying the long-term impacts of CA or expanding trials to different climatic zones could provide better trends.

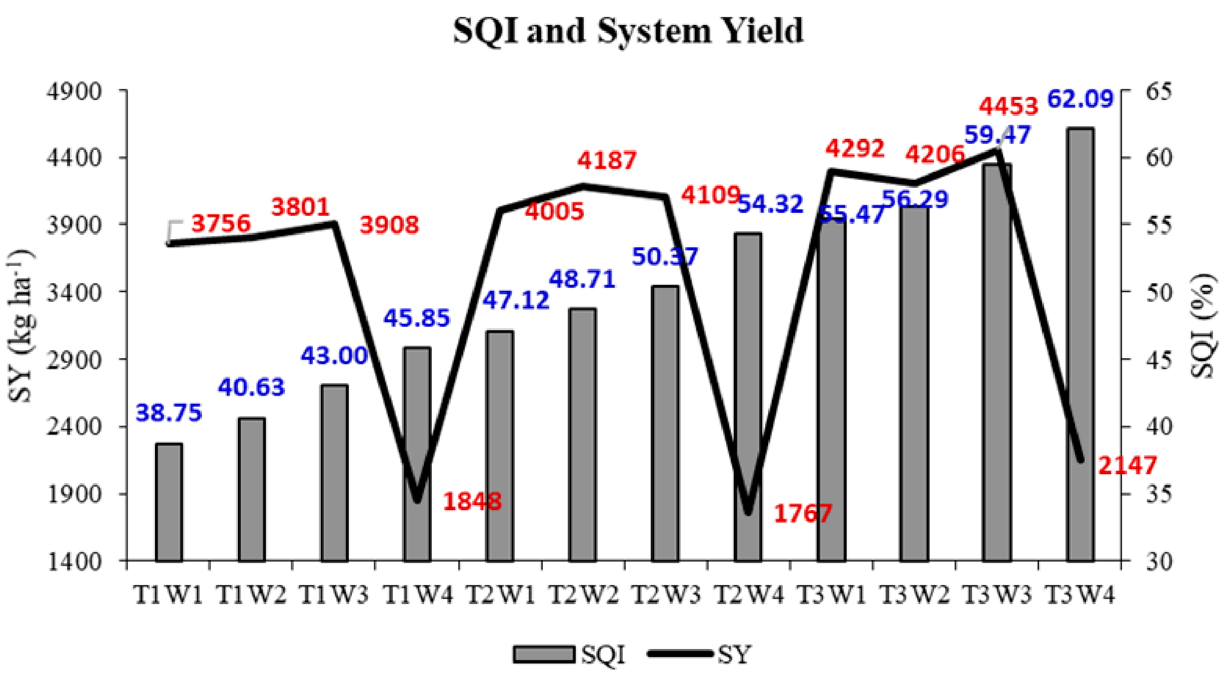

Figure 4. Relationship between soil quality index (SQI) and system yield (SY) in terms of cotton equivalent yield (CEY) in tillage and weed management treatment combinations (2022–2023). Main treatments: T_1 = conventional tillage (cotton)–conventional tillage (maize)–fallow (no *Sesbania rostrata*), 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.

8. Conclusions

On the basis of the 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 ZT(C) + *Sr*R-ZT(M) + CR-ZT(*Sr*) + MS 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 optimizing 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 an 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 the potential to enhance and maintain soil and agro-ecology, as well as agro-ecosystem resilience, while improving soil quality and crop productivity. This information garnered in this present investigation is very crucial to offering actionable insights for farmers and policymakers to adopt conservation agriculture practices, particularly in resource-constrained and semi-arid regions, and to deeply understand the development of soil quality and associated agro-ecosystem services.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17030978/s1, Table S1: Experiment particulars. Table S2: Characteristics of cotton, maize and Sesbania cultivars used. Table S3. Soil physical properties. Table S4. Soil physico-chemical, chemical/ and fertility properties. Table S5. Soil biological properties. Table S6: Scoring curve of different soil parameters considered for computation of SQI. Table S7: Grain Yield of maize and seed cotton yield as influenced by tillage practices and weed management (WM) options after 3 years under conservation agriculture. Table S8: Impact of tillage practices and weed management option interactions on rhizosphere dehydrogenase activity; DHA (µg TPF.g^{-1} dry soil.day^{-1}), urease activity; SUA (µg NH_4^+-N.g^{-1} dry soil.2 h^{-1}), Acid phosphatase activity; AcPA (µg. *p*-nitrophenol. g^{-1} dry soil. h^{-1}), Alkaline phosphatase activity; AlPA (µg. *p*-nitrophenol. g^{-1} dry soil. h^{-1}), Fluorescein di-acetate activity; FDA (µg. fluorescein. g^{-1} dry soil.3 h^{-1}), β-galactosidase activity; β-GaA (nmol *p*-nitrophenol. g^{-1} dry soil.h^{-1}) at tasseling (60 DAS) stage of maize. Table S9: Impact of tillage practices and weed management option interactions on rhizosphere *Azotobacter* ($\times 10^3$ CFU g^{-1} soil) population, *Azospirillum* population ($\times 10^3$ CFU g^{-1} soil) and fungal population ($\times 10^3$ CFU g^{-1} soil) at tasseling stage (60 DAS) of maize. Table S10: Correlation matrix showing the effect of tillage practices and weed management options on soil quality variables. Figure S1: Satellite view of the experimental field (36 plots inside demarcated with yellow line). Figure S2: Weekly-base mean meteorological observations during maize development. Figure S3: Weekly-base mean meteorological observations during cotton development. References [52–85] are cited in supplementary materials.

Author Contributions: Research conceptualization, methodology, discussion and figures preparation, supervision and editing main manuscript text, supervision of field investigation: K.N., R.T. and P.B., investigation, data collection and extraction, interpretation of results and review of literature evaluation: L.P.C., J.G. and N.K.S., statistical analysis of data and draft writing, design and supervision: M.A., investigation, data collection and processing: T.B.S. and K.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors".

Informed Consent Statement: All authors are informed and provided consent for this submission.

Data Availability Statement: Data are provided within the manuscript or Supplementary Information files.

Acknowledgments: The authors are extremely thankful to All India Coordinated Research Project (AICRP) on weed management for the financial sponsorship received for the implementation and execution of this on-going conservation agriculture experiment, carried out at the college farm of Professor Jayashankar Telangana State Agricultural University (PJTSAU), Rajendranagar, Telangana, India.

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

References

1. Nthebere, K.; Ram Prakash, T.; Jayasree, G.; Padmaja, B.; Meena, A.; Latha, P.C. Impact of Conservation Agricultural Practices on Depth-wise Distribution of Soil Physico-chemical Attributes and available Soil Nutrients under Cotton-Maize-*Sesbania rostrata* Cropping System. *Biol. Forum–Int. J.* **2023**, *15*, 496–502.
2. Nadathur, S.R.; Wanasundara, J.P.D.; Scanlin, L. Proteins in the diet: Challenges in feeding the global population. In *Sustainable Protein Sources*; Academic Press: Cambridge, MA, USA, 2017; pp. 1–19.
3. Nthebere, K.; Bhatt, R. Resource conservation technologies for reduced water footprints and higher input use efficiencies. *AgriGate-Int. Multidiscip. E-Mag.* **2024**, *4*, 407–412.
4. Suarez, R.P.; Goijman, A.P.; Cappelletti, S.; Solari, L.M.; Cristos, D.; Rojas, D.; Krug, P.; Babbitt, K.J.; Gavier-Pizzaro, G.I. Combined effects of agrochemical contamination and forest loss on anuran diversity in agroecosystems of east-central Argentina. *Sci. Total Environ.* **2021**, *759*, 14. [CrossRef]
5. Ansari, M.A.; Choudhury, B.U.; Layek, J.; Das, A.; Lal, R.; Mishra, V.K. Green manuring and crop residue management: Effect on soil organic carbon stock, aggregation, and system productivity in the foothills of Eastern Himalaya (India). *Soil Tillage Res.* **2022**, *218*, 105318. [CrossRef]
6. Panwar, A.S.; Ansari, M.A.; Ravisankar, N.; Babu, S.; Prusty, A.K.; Ghasal, P.C.; Choudhary, J.; Shamim, M.; Singh, R.; Raghavendra, K.J.; et al. Effect of organic farming on the restoration of soil quality, ecosystem services, and productivity in rice–wheat agro-ecosystems. *Front. Environ. Sci.* **2022**, *10*, 972394. [CrossRef]
7. Nthebere, K.; Prakash, T.R.; Kumar, N.V.; Yadav, M.B.N. Capability of conservation agriculture for preservation of organic carbon and succeeding effect on soil properties and productivity—A review. *Arch. Agron. Soil Sci.* **2024**, *70*, 1–28. [CrossRef]
8. Mrabet, R.; Singh, A.; Sharma, T.; Kassam, A.; Friedrich, T.; Basch, G.; Gonzalez-Sanchez, E. *Conservation Agriculture: Climate Proof and Nature Positive Approach*; IntechOpen: London, UK, 2022; pp. 1–15.
9. Kassam, A.; Friedrich, T.; Derpsch, R. Successful experiences and lessons from conservation agriculture worldwide. *Agronomy* **2022**, *12*, 769. [CrossRef]
10. FAO. *Conservation Agriculture*; FAO: Rome, Italy, 2022; Available online: https://www.fao.org/3/i4009e/i4009e (accessed on 5 December 2024).
11. Nthebere, K.; Sharma, S.H.K.; Kumari, C.P.; Qureshi, A.A. Long-term effect of different cropping systems on carbon sequestration in a sandy loam soil of Telangana. *Agric. Rev.* **2022**, *43*, 249–254. [CrossRef]
12. Singh, A.K.; Bordoloi, L.J.; Kumar, M.; Hazarika, S.; Parmar, B. Land use impact on soil quality in Eastern Himalayan region of India. *Environ. Monit. Assess.* **2013**, *186*, 2013–2024. [CrossRef]
13. Duddigan, S.; Shaw, L.J.; Sizmur, T.; Dharmendar, G.; Zakir, H.; Kiranma, J.; Hamilka, K.; Rahul, S.; Mohammad, S.; Reshma, S.; et al. Natural farming improves crop yield in SE India when compared to conventional or organic systems by enhancing soil quality. *Agron. Sustain. Dev.* **2023**, *43*, 31. [CrossRef]
14. Ponnusamy, J.; Santhy Poongavanam, L.K.; Ettiyagounder, P.; Murugesan, M.; Ramanujam, K.; Rangasamy, S.; Shanmugam, K.P. Impact of regenerative farming practices on soil quality and yield of cotton-sorghum system in semi-arid Indian conditions. *Environ. Monit. Assess.* **2024**, *196*, 462. [CrossRef] [PubMed]
15. Masto, R.E.; Chhonkar, P.K.; Singh, D.; Patra, A.K. Soil quality response to long term nutrient and crop management on a semi-arid Inceptisol. *Agric. Ecosyst. Environ.* **2007**, *118*, 130–142. [CrossRef]
16. Aziz, I.; Mahmood, T.; Islam, K.R. Effect of long term no-till and conventional tillage practices on soil quality. *Soil Tillage Res.* **2013**, *131*, 28–35. [CrossRef]
17. Choudhary, M.; Jat, H.S.; Datta, A.; Yadav, A.K.; Sapkota, T.B.; Mondal, S.; Meena, R.P.; Sharma, P.C.; Jat, M.L. Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. *Appl. Soil Ecol.* **2018**, *126*, 189–198. [CrossRef]
18. Kumar, A.; Somasundaram, J.; Biswas, A.K.; Sinha, N.K.; Mishra, V.N.; Chaudhary, R.S.; Patra, A.K. Short-term effect of conservation agriculture practices on soil quality of a vertisol in central India. *Appl. Biol. Res.* **2017**, *19*, 26–34. [CrossRef]
19. Roy, D.; Datta, A.; Jat, H.S.; Choudhary, M.; Sharma, P.C.; Singh, P.K.; Jat, M.L. Impact of long-term conservation agriculture on soil quality under cereal based systems of North West India. *Geoderma* **2022**, *405*, 115391. [CrossRef]

20. Bolinder, M.A.; Janzen, H.H.; Gregorich, E.G.; Angers, D.A.; VandenBygaart, A.J. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agric. Ecosyst. Environ.* **2007**, *118*, 29–42. [CrossRef]
21. Kumari, C.P.; Goverdhan, M.; Nthebere, K.; Reddy, G.K.; Sharma, S.H.K.; Qureshi, A.A.; Alibaba, M.; Chiranjeevi, K. Diversification of Cropping Systems for Different Integrated Farming System Models under Irrigated Situation of Southern Telangana Zone, Telangana, India. *Curr. J. Appl. Sci. Technol.* **2020**, *39*, 51–60. [CrossRef]
22. Prajapati, S.K.; Dayal, P.; Kumar, V.; Gairola, A. Green Manuring: A Sustainable Path to Improve Soil Health and Fertility. *Int. J.* **2023**, *1*, 24–33.
23. Song, S.; Yin, Q.; Khan, M.N.; Zhao, T.; Liu, K.; Harrison, M.T.; Tao, Y.; Nie, L. Green manuring improves soil quality, grain yield, and grain anthocyanin content in colored rice cultivated in tropical regions. *Food Energy Secur.* **2024**, *13*, e571. [CrossRef]
24. Wu, X.; Yao, Z.; Brüggemann, N.; Shen, Z.Y.; Wolf, B.; Dannenmann, M.; Butterbach-Bahl, K. Effects of soil moisture and temperature on CO_2 and CH_4 soil–atmosphere exchange of various land use/cover types in a semi-arid grassland in Inner Mongolia, China. *Soil Biol. Biochem.* **2010**, *42*, 773–787. [CrossRef]
25. Mukherjee, A.; Lal, R. Comparison of soil quality index using three methods. *PLoS ONE* **2014**, *9*, e105981. [CrossRef] [PubMed]
26. Panse, V.G.; Sukhatme, P.V. *Statistical Methods for Agricultural Works*; ICAR: New Delhi, India, 1978.
27. Mohanty, M. *SQI CAL Software—A Tool for Soil Health Assessment*; Division of Soil Physics, Indian Institute of Soil Science: Bhopal, India, 2020.
28. Six, J.; Elliott, E.T.; Paustian, K. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no tillage agriculture. *Soil Biol. Biochem.* **2000**, *32*, 2099–2103. [CrossRef]
29. Bandyopadhyay, P.K.; Saha, S.; Mani, P.K.; Mandal, B. Effect of organic inputs on aggregate associated organic carbon concentration under long-term rice–wheat cropping system. *Geoderma* **2010**, *154*, 379–386. [CrossRef]
30. Choudhury, S.G.; Srivastava, S.; Singh, R.; Chaudhari, S.K.; Sharma, D.K.; Singh, S.K.; Sarkar, D. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. *Soil Tillage Res.* **2014**, *136*, 76–83. [CrossRef]
31. Boogar, A.M.; Jahansouz, M.R.; Reza, M. Soil aggregate size distribution and stability following conventional-till, minimum-till and no-till systems. *Int. J. Farming Allied Sci.* **2014**, *3*, 512–517.
32. Koorneef, G.J.; Pulleman, M.M.; Comans, R.N.; Van Rijssel, S.Q.; Barré, P.; Baudin, F.; De Goede, R.G. Assessing soil functioning: What is the added value of soil organic carbon quality measurements alongside total organic carbon content? *Soil Biol. Biochem.* **2024**, *196*, 109507. [CrossRef]
33. Nthebere, K.; Prakash, T.R.; Bhimireddy, P.; Chandran, L.P.; Gudapati, J.; Admala, M.; Prasad, K. Conservation agricultural practices promoted arbuscular mycorrhizal fungal colonization and glomalin content on sandy clay loam of southern India. *Heliyon* **2024**, *11*, e41196. [CrossRef]
34. Sapre, N.; Singh, P.; Kewat, M.L.; Sharma, A.R. The cumulative effect of tillage and weed management practices on soil property, weed dynamics and productivity of mungbean (*Vigna radiata* L.) in the rice-wheat-mungbean cropping system. *J. Pharmacogn. Phytochem.* **2019**, *8*, 1881–1886.
35. Nthebere, K.; Ram Prakash, T.; Jayasree, G.; Padmaja, B.; Meena, A.; Latha, P.C. Changes in Soil Physical Properties and Available Micronutrients as Influenced by Tillage and Weed Management Strategies under Diversified Cropping System. *Biol. Forum–Int. J.* **2023**, *15*, 131–140.
36. Thakur, P.; Paliyal, S.S.; Dev, P.; Datt, N. Methods and approaches—Soil quality indexing, minimum data set selection and interpretation—A Critical Review. *Commun. Soil Sci. Plant Anal.* **2022**, *53*, 1849–1864. [CrossRef]
37. Zeraatpisheh, M.; Bakhshandeh, E.; Hosseini, M.; Alavi, S.M. Assessing the effects of deforestation and intensive agriculture on the soil quality through digital soil mapping. *Geoderma* **2020**, *363*, 114139. [CrossRef]
38. Stenberg, B. Monitoring soil quality of arable land: Microbiological indicators. *Acta Agric. Scand. Sect. B-Plant Soil Sci.* **1999**, *49*, 1–24. [CrossRef]
39. Chaer, G.; Fernandes, M.; Myrold, D.; Bottomley, P. Comparative resistance and resilience of soil microbial communities and enzyme activities in adjacent native forest and agricultural soils. *Microb. Ecol.* **2009**, *58*, 414–424. [CrossRef]
40. Adetunji, A.T.; Lewu, F.B.; Mulidzi, R.; Ncube, B. The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: A review. *J. Soil Sci. Plant Nutr.* **2017**, *17*, 794–807. [CrossRef]
41. Schröder, P.; Beckers, B.; Daniels, S.; Gnädinger, F.; Maestri, E.; Marmiroli, N.; Mench, M.; Millan, R.; Obermeier, M.; Oustriere, N. Intensify production, transform biomass to energy and novel goods and protect soils in Europe—A vision how to mobilize marginal lands. *Sci. Total Environ.* **2018**, *616*, 1101–1123. [CrossRef]
42. Nayak, D.R.; Babu, Y.J.; Adhya, T. Long-term application of compost influences microbial biomass and enzyme activities in a tropical Aeric Endoaquept planted to rice under flooded condition. *Soil Biol. Biochem.* **2007**, *39*, 1897–1906. [CrossRef]
43. Neina, D. The role of soil pH in plant nutrition and soil remediation. *Appl. Environ. Soil Sci.* **2019**, *2019*, 5794869. [CrossRef]

44. Swarup, A. Effect of presubmergence and green manuring (Sesbaniaaculeata) on nutrition and yield of wetland rice (Oryza sativa L.) on a sodic soil. *Biol. Fertil. Soils* **1987**, *5*, 203–208. [CrossRef]
45. Touhami, D.; McDowell, R.W.; Condron, L.M. Role of organic anions and phosphatase enzymes in phosphorus acquisition in the rhizospheres of legumes and grasses grown in a low phosphorus pasture soil. *Plants* **2020**, *9*, 1185. [CrossRef]
46. Ramprakash, T.; Padmaja, B.; Nthebere, K.; Chopde, V.; Mishra, J.S.; Dubey, R.P. Weed management and conservation agriculture in cotton-based systems: Implications on soil quality and climate change mitigation. *Indian J. Weed Sci.* **2024**, *56*, 426–438.
47. Padbhushan, R.; Kumar, U.; Sharma, S.; Rana, D.S.; Kumar, R.; Kohli, A.; Kumari, P.; Parmar, B.; Kaviraj, M.; Sinha, A.K. Impact of land-use changes on soil properties and carbon pools in India: A meta-analysis. *Front. Environ. Sci.* **2022**, *9*, 794866. [CrossRef]
48. Moebius, B.N.; van Es, H.M.; Schindelbeck, R.R.; Idowu, O.J.; Clune, D.J.; Thies, J.E. Evaluation of laboratory-measured soil properties as indicators of soil physical quality. *Soil Sci.* **2007**, *172*, 895–912. [CrossRef]
49. Cerbari, V. The program for development and implementation of conservative technologies in Agriculture. *Agric. Mag. Mold.* **2011**, *4–5*, 7–9.
50. Kumar, S.; Rana, S.S.; Kumar, R.; Sharma, N. Effects of Conservation Tillage and Weed Management On Soil Microbial Community and Enzymatic Activity. *Bangladesh J. Bot.* **2022**, *51*, 425–431. [CrossRef]
51. Dass, A.; Shekhawat, K.; Choudhary, A.K.; Sepat, S.; Rathore, S.S.; Mahajan, G.; Chauhan, B.S. Weed management in rice using crop competition-a review. *Crop Prot.* **2017**, *95*, 45–52. [CrossRef]
52. Gee, W.G.; Or, D. Particle-Size Analysis. In *Methods of Soil Analysis*; Dane, J., Topp, G.C., Eds.; Book Series: 5. Part 4; Soil Science Society of America: Madison, WI, USA, 2002; pp. 255–293.
53. Yoder, R.E. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *J. Am. Soc. Agron.* **1936**, *28*, 337–351. [CrossRef]
54. Blake, G.R.; Hartge, K.H. Bulk density. *Methods Soil Anal. Part 1 Phys. Mineral. Methods* **1986**, *5*, 363–375.
55. Klute, A.; Driksen, C. Hydraulic conductivity and diffusivity: Laboratory methods. *Methods Soil Anal. Part 1 Phys. Mineral. Methods* **1986**, *5*, 687–734.
56. Anderson, G.; Pidgeon, J.D.; Spencer, H.B.; Parks, R. A new hand-held recording penetrometer for soil studies. *J. Soil Sci.* **1980**, *31*, 279–296. [CrossRef]
57. Bouwer, H. Intake rate: Cylinder infiltrometer. *Methods Soil Anal. Part 1 Phys. Mineral. Methods* **1986**, *5*, 825–844.
58. Keen, B.A.; Raczkowski, H. The relation between the clay content and certain physical properties of a soil. *J. Agric. Sci.* **1921**, *11*, 441–449. [CrossRef]
59. Fornasier, E.; Fornasier, F.; Di Marco, V. Spectrophotometric methods for the measurement of soil pH: A reappraisal. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2018**, *204*, 113–118. [CrossRef] [PubMed]
60. Ratshiedana, P.E.; Abd Elbasit, M.A.; Adam, E.; Chirima, J.G.; Liu, G.; Economon, E.B. Determination of soil electrical conductivity and moisture on different soil layers using electromagnetic techniques in irrigated arid environments in South Africa. *Water* **2023**, *15*, 1911. [CrossRef]
61. Bower, C.A.; Reitemeier, R.F.; Fireman, M. Exchangeable cation analysis of saline and alkali soils. *Soil Sci.* **1952**, *73*, 251–262. [CrossRef]
62. Walkley, A.; Black, C.A. Estimation of organic carbon by chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
63. Subbiah, B.V.; Asija, G.L. A rapid procedure for the determination of available nitrogen in soils. *Curr. Sci.* **1956**, *25*, 259–260.
64. Olsen, S.R. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate (No. 939)*; US Department of Agriculture: Washington, DC, USA, 1954.
65. Fu, X.; Zhao, C.; Ma, S.; Tian, H.; Dong, D.; Li, G. Determining available potassium in soil by laser-induced breakdown spectroscopy combined with cation exchange membrane adsorption. *J. Anal. At. Spectrom.* **2020**, *35*, 2697–2703. [CrossRef]
66. Lindsay, W.L.; Norvell, W.A. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.* **1978**, *42*, 421–428. [CrossRef]
67. Chan, K.Y.; Bowman, A. Oxidizable organic carbon fractions and soil quality changes in Oxic Paleustalf under different pasture leys. *Soil Sci.* **2001**, *166*, 61–67. [CrossRef]
68. Jha, P.; Biswas, A.K.; Lakaria, B.L.; Saha, R.; Singh, M.; Rao, A.S. Predicting total organic carbon content of soils from Walkley and Black analysis. *Commun. Soil Sci. Plant Anal.* **2014**, *45*, 713–725. [CrossRef]
69. Dean, W.E. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *J. Sediment. Res.* **1974**, *44*, 242–248.
70. Bremner, J.M.; Mulvaney, C.S. Total nitrogen. *Methods Soil Anal. Part 2 Chem. Microbiol. Prop.* **1982**, *9*, 595–624.
71. Dobereiner, J.; Marriel, I.E.; Nery, M. Ecological distribution of *Spirillum lipoferum Beijerinck*. *Can. J. Microbiol.* **1976**, *22*, 1464–1473. [CrossRef]
72. Jensen, H.L. Notes on the biology of Azotobacter. *Proc. Soc. Appl. Bacteriol.* **1951**, *14*, 89. [CrossRef]
73. Thorton, H.G. On the development of a standardized agar tor counting soil bacteria with especial regard to the repression of spreading colonies. *Ann. Appl. Biol.* **1922**, *9*, 241–274. [CrossRef]

74. Martin, J.P. Use of acid, rose bengal and streptomycin in the plate method for estimating soil fungi. *Soil Sci.* **1950**, *69*, 215. [CrossRef]
75. Allen, O.N. *Experiments in Soil Bacteriology*; Burgess Publication Company: Minneapolis, MI, USA, 1957; pp. 202–238.
76. Tabatabai, M.A.; Bremner, J.M. Assay of Urease Activity in Soils. *Am. J. Soil Sci. Soc.* **1972**, *41*, 350–352. [CrossRef]
77. Tabatabai, M.A.; Bremner, J.M. Use of *P*-nitrophenyl Phosphate for Assay of Soil Phosphatase Activity. *Soil Biol. Biochem.* **1969**, *1*, 301–307. [CrossRef]
78. Eivazi, F.; Tabatabai, M.A. Glucosidases and galactosidases in soils. *Soil Biol. Biochem.* **1988**, *20*, 601–606. [CrossRef]
79. Green, V.S.; Stott, D.E.; Diack, M. Assay for fluorescein diacetate hydrolytic activity: Optimization for soil samples. *Soil Biol. Biochem.* **2006**, *38*, 693–701. [CrossRef]
80. Casida, L.E.; Klein, D.A.; Santaro, T. Soil dehydrogenase activity. *Soil Sci.* **1964**, *98*, 371–376. [CrossRef]
81. Beck, T.; Joergensen, R.G.; Kandeler, E.; Makeschin, F.; Nuss, E.; Oberholzer, H.R.; Scheu, S. An inter-laboratory comparison of ten different ways of measuring soil microbial biomass C. *Soil Biol. Biochem.* **1997**, *29*, 1023–1032. [CrossRef]
82. Witt, C.; Gaunt, J.L.; Galicia, C.C.; Ottow, J.C.; Neue, H.U. A rapid chloroform-fumigation extraction method for measuring soil microbial biomass carbon and nitrogen in flooded rice soils. *Biol. Fertil. Soils* **2000**, *30*, 510–519. [CrossRef]
83. Brookes, P.C.; Landman, A.; Pruden, G.; Jenkinson, D.S. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biol. Biochem.* **1985**, *17*, 837–842. [CrossRef]
84. Amato, M.; Ladd, J.N. Assay for microbial biomass based on ninhydrin-reactive nitrogen in extracts of fumigated soils. *Soil Biol. Biochem.* **1988**, *20*, 107–114. [CrossRef]
85. Da-Silva, E.E.; Azevedo, P.H.S.; De-Polli, H. *Determinação da Respiração basal (RBS) e Quociente Metabólico do Solo (qCO_2)*; Comunicado Técnico EMBRAPA: São Paulo, Brazil, 2007; pp. 1–4.