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Soil Carbon and Biochemical Indicators of Soil Quality as Affected by Different Conservation Agricultural and Weed Management Options

Gobinder Singh [1], Kuldeep Raj Sharma [2], Rajan Bhatt [3], Jagdeep Singh [1], Owais Ali Wani [2], Ahmed Z. Dewidar [4,5] and Mohamed A. Mattar [4,5,*]

[1] Department of Soil Science, Punjab Agricultural University, Ludhiana 141004, India; gobinder-kpr@pau.edu (G.S.); jagdeep_76@pau.edu (J.S.)
[2] Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180009, India; krmansotra2006@yahoo.co.in (K.R.S.); owaisaliwani@skuastkashmir.ac.in (O.A.W.)
[3] PAU-Krishi Vigyan Kendra, Amritsar 143601, India; rajansoils@pau.edu
[4] Prince Sultan Bin Abdulaziz International Prize for Water Chair, Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, P.O. Box 2454, Riyadh 11451, Saudi Arabia; adewidar@ksu.edu.sa
[5] Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia
* Correspondence: mmattar@ksu.edu.sa

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Abstract: Burning of agricultural residues, cultivation of single crop varieties such as rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.), and traditional soil tillage practices collectively contribute to the degradation of environmental quality, water systems, and soil resources. To address these issues, conservation agriculture (CA)-based crop management practice has emerged as one of the viable options. The current study was conducted with the aim to evaluate the effect of CA and weed management (WM) practices on carbon dynamics and biochemical properties of soil. The experiment included two factors, viz., CA and WM practices. The CA levels vary from conventional agriculture to partial CA (pCA1, pCA2, and pCA3) and full CA, while WM had three levels consisting of chemical control, integrated weed management, and weedy check. The results demonstrated that soil organic carbon (SOC) under the full CA treatment, was 30.6, 23.5, and 20.6 percent higher than conventional agriculture (T1), partial CA1, and partial CA2 practices, respectively. Similarly, labile fractions of carbon, $KMnO_4$-C MBC, WSOC, and POC, in full CA increased by 46.3, 52.3, 152.4, and 15.6 percent, respectively, over conventional agriculture. Nonetheless, the total organic carbon exhibited no significant impact. The highest SOC stock was sequestered under full CA treatment, which was higher by 26.5 to 40.6 per cent than the rest of the CA treatments. Among biological properties, full CA resulted in 104.3 and 40.6 percent higher dehydrogenase and alkaline phosphatase activity than conventional agriculture. The impact of weed management practices was significant for $KMnO_4$-C, with very labile carbon and alkaline phosphatase activity only in the surface soil layer. Soil quality index (SQI) followed the decreasing order as full CA (0.94) > partial CA3 (0.88) > partial CA2 (0.78) partial CA1 (0.77) > conventional agriculture (0.67) under different CA treatments, whereas WM followed herbicide (0.82) > weedy check (0.81) > IWM (0.80). The current study offered incredible information on soil carbon and biological indicators to monitor soil quality changes in rice–wheat cropping systems in response to conservation agriculture practices.

Keywords: soil organic carbon; conservation agriculture; labile carbon; soil quality; weed management

1. Introduction

The rice–wheat cropping system is one of the world's largest cropping systems and is very crucial for food security [1]. This cropping strategy has gained popularity due to its profitability even in light textured soils. The large-scale adoption of RWCS during the past four decades had given rise to "second-generation challenges" [2] such as declining water table [3], subsurface compaction [4], development of herbicide resistance [5], declining organic carbon content [6,7], and multi-nutrient deficiency [8]. To overcome these challenges, proper planning and execution of strategic initiatives are crucial for the replenishment of gradually deteriorating natural resources and sustainable crop production, soil health, and production environment in the RWCS [9]. To address the aforementioned problems, conservation agriculture (CA)-based technologies have been developed and are now being promoted [10]. With this approach, minimal soil disturbance and covering the soil with cover crops, crop residues, and crop rotations are applied to enhance productivity along with improving soil health [11]. Along with productivity, CA plays an important role in enhancing carbon inputs [12], the buildup of soil organic carbon [13], regulation of soil temperature, conservation of soil moisture, reducing greenhouse gases emission [14], lessening soil degradation, and offering substrate for soil microbes [15]. The diverse soil management practices under CA appeared to have a significant impact on fractions of carbon; however, labile C fractions such as permanganate oxidizable carbon [16], particulate organic carbon [17], water soluble organic carbon [18], and microbial biomass carbon [19] were susceptible to change earlier as compared to the recalcitrant pool of carbon such as total organic carbon [20]. The labile C fractions contributed significantly to the priming effect of soil [21]. Active pools of carbon encompass the organic carbon stored in the soil, plant biomass, and atmosphere, and are vital for global carbon cycling and climate stability. Conservation agriculture practices have a significant impact on carbon pools by fostering soil carbon sequestration, mitigating carbon emissions, and bolstering ecosystem resilience [22]. Numerous studies have examined the impact of conservation agriculture (CA) on carbon pools. Smith et al. [23] observed a yearly average increase of 0.3 per cent in soil organic carbon stocks through CA practices across different agricultural systems. Lal [22] reported that adopting CA techniques led to a soil carbon sequestration increase of 0.4–0.6 tons per hectare per year. Therefore, the assessment of labile fractions of carbon could offer a more sensitive appraisal and an indication of the impact of tillage and residue management practices on soil quality [24,25].

One of the most intensive management techniques used in various crop production systems is weed control, which has an impact on both the environment and agricultural output. The direct and indirect effects of weed control on soil quality can range from detrimental to beneficial. Various weed management techniques affect a variety of soil parameters, including rhizospheric and bulk soil nutrients, rhizodeposition, soil organic carbon (SOC), soil pH, moisture, soil enzyme activity, and many more [26]. Higher production could result from combining weed management techniques with conservation agricultural concepts.

We hypothesize that CA will increase soil carbon and improve soil quality index in soils of northwestern India. Additionally, integrating different weed management practices within CA system is expected to further enhance these effects.

Hence, the current study was conducted to (a) evaluate the impact of CA and weed management practices on carbon dynamics, (b) assess the role of CA and weed management on biochemical properties of soil, and (c) evaluate the impact of CA and weed management practices on soil quality.

2. Materials and Methods

2.1. Study Site

In 2015, the experiment was launched in the SKUAST-Jammu field in Chatha, J&K. The experimental location, which represents the sub-tropical zone of Jammu province, is located at 32°40′ N latitude and 78°48′ E longitude at a height of 293 m above mean sea level (Figure 1). It belongs to the Jammu area of J&K's agroclimatic zone 1 (Western Himalayan). The climate at Chatha throughout the growing season was ideally suited for typical development and growth. The experimental location witnessed 1251 mm of yearly rainfall on average, with 85–90% of that total falling during the rainy season (June to September). At typical monthly temperatures of 36.5 and 3.9 °C, respectively, June and January were the hottest and coldest months. The soil (*Inceptisol* according to USDA soil classification) has a sandy clay loam texture, is non-saline, and reacts neutrally to mildly alkaline. The plough layer had 57.32 percent sand, 22.0 percent silt, and 20.68 percent clay. Olsen's phosphorus (6.8 mg kg^{-1}), ammonium acetate (NH_4OAc)-extractable potassium (63.0 mg kg^{-1}), and permanganate ($KMnO_4$) oxidizable nitrogen (101.3 mg kg^{-1}) were all moderately present in the soil. Soil organic carbon (SOC) content before the start of the experiment was 4.9 g kg^{-1} in 0–15 cm soil layer using Walkley and Black as per prescribed procedures.

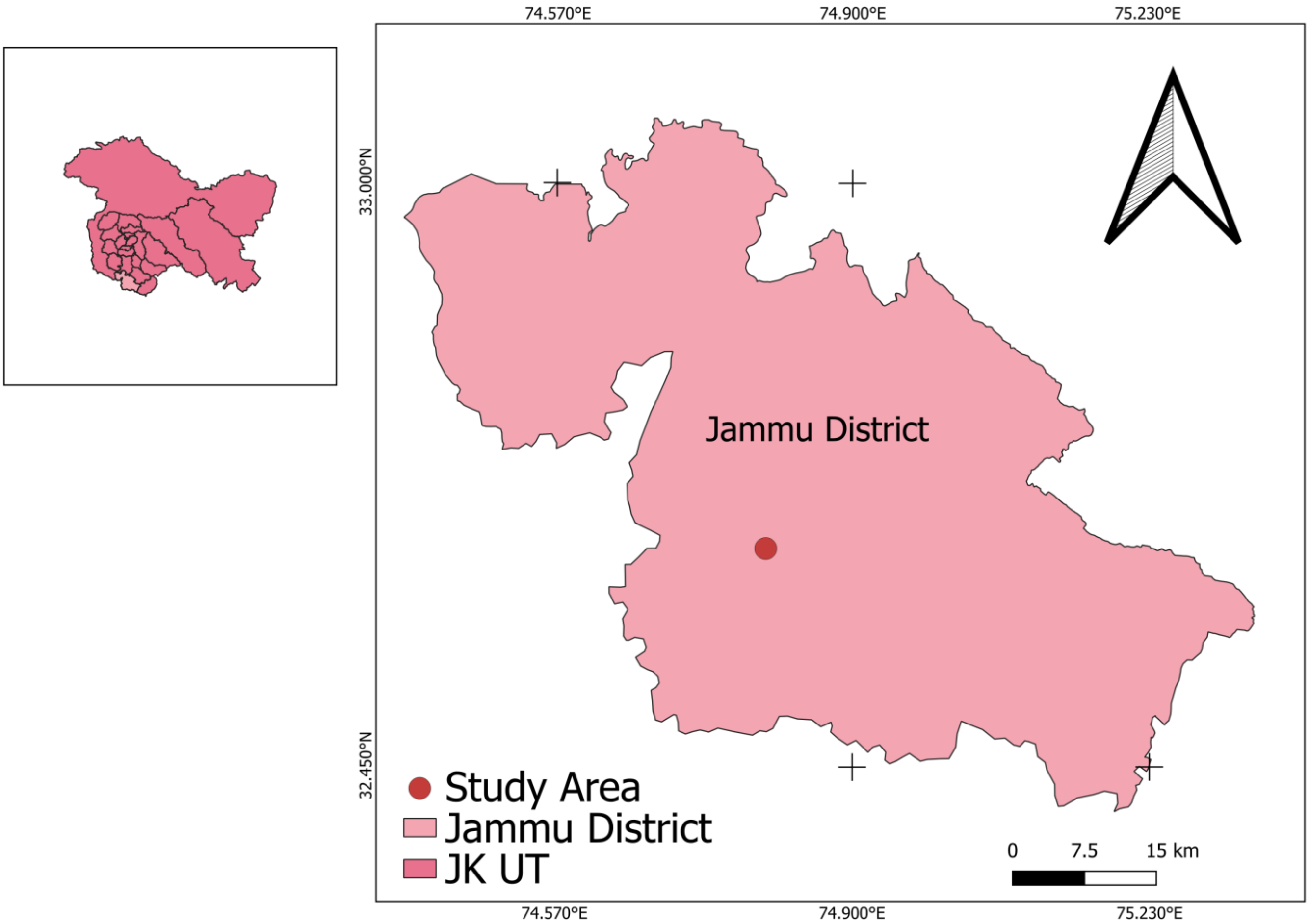

Figure 1. Description of study site.

2.2. *Treatments*

The experiment was laid out in factorial RBD with two factors. The first factor (CA) comprises five levels and the second factor (weed management) comprises three levels the details are given in the Table 1. The plot size of the experiment was 5 m × 2 m.

Table 1. Description of different conservation agriculture (CA) and weed management (WM) treatments used in the study.

Treatment	Crop	Crop Establishment Method	Previous Crop Residue Removed or Retained
T1 (Conventional agriculture) CTR-CTW	Rice	Conventional-transplanted rice (CTR)	Wheat residue removed (−WR)
	Wheat	Conventional-tilled (CT) wheat	Rice residue removed (−RR)

Table 1. *Cont.*

Treatment	Crop	Crop Establishment Method	Previous Crop Residue Removed or Retained
T2 (Partial CA 1) CTR-ZTW-ZTG	Rice Wheat Green gram	Conventional-transplanted rice Zero-till (ZT) wheat Zero-tilled green gram	Green gram residue incorporated Rice residue removed (−RR) Wheat residue removed (−WR)
T3 (Partial CA 2) CTDSR -CTW-ZTG	Rice Wheat Green gram	Conventional-tilled direct seeded rice Conventional-tilled wheat Zero-tilled green gram	Green gram residue incorporated Rice residue removed (−RR) Wheat residue removed (−WR)
T4 (Partial CA 3) ZTDQSR-ZTW-ZTG	Rice Wheat Green gram	Zero-till direct seeded rice Zero-tilled wheat Zero-tilled green gram	Green gram residue retained as brown manure Rice residue retained as mulch in wheat (+RR) Wheat straw removed(-WR)
T5 (Full CA) ZTDSR-ZTW-ZTG	Rice Wheat Green gram	Zero-till direct seeded rice Zero-tilled wheat Zero-tilled green gram	Green gram residue retained as brown manure crop Rice residue retained as mulch in wheat (+RR) Wheat residue retained (+WR)
Weed Management (WM) Treatments			
Treatment		Rice	Wheat
Chemical weed control (Herbicide)		Pre-emergence application of Pendimethalin 30 EC @1250 mL ha^{-1} and post-emergence application after 25 days of sowing, bispyribac-sodium 25 g a.i./ha	Pre-emergence application of Pendimethlin 30 EC @1250 mL ha^{-1} and after 30 days of sowing, clodinafop (15%) + metsulfuron methyl (1%) 60 + 4 g a.i./ha was applied as post-emergence with knap sac sprayer fitted with flat fan boom nozzle.
Integrated weed management (IWM)		Chemical weed control + 1 hand weeding	Chemical weed control + 1 hand weeding
Weedycheck		No weed control	No weed control

2.3. Crop Management

For rice, under conventional transplanted rice (CTR) treatments, seedlings were raised using seed rate of 20 kg ha^{-1} and residue of preceding wheat was removed. Pre-puddling tillage operations included two disc-ploughings and two harrowings followed by plankings. Puddling (wet tillage) was performed twice in 6–8 cm of standing water using a tractor-mounted puddler followed by planking. Rice seedlings were manually transplanted at 15 × 20 cm spacing. Under CTDSR, the leftover residue from the previous wheat crop is removed. The tillage process for DSR involves using two passes of harrows and two passes of tyne plough, followed by leveling. The DSR is then sown using an inclined plate multi-crop planter, with the rows spaced 20 cm apart. Under ZTDSR, Zero-till DSR was sown using inclined plate multi-crop planter in rows 20 cm apart without any preparatory tillage.

During the wheat cycle, under conventional tilled wheat (CTW), two passes of harrows and two passes of tyne plough followed by plankings. After pre-sowing irrigation, the seed bed was prepared by two passes of tyne plough followed by planking. Wheat was sown with a seed-cum-fertilizer drill at row spacing of 20 cm by using seed rate of 100 kg ha^{-1}. However, under ZTW, wheat was directly seeded in the no-till plots in rows 20 cm apart using a zero-till seed-cum-fertilizer drill. Green gram was sown with a zero-till drill with rows 20 cm apart by using seed rate of 37.5 kg ha^{-1}. Irrespective of the treatments, wheat variety HD 2967, basmati variety Pusa 1121, and green gram variety SML 668 were used for sowing. The wheat crop was sown during the first fortnight of November every year and green gram was sown after the harvesting of wheat, whereas basmati rice was directly seeded after the harvesting of green gram and transplanted during the second fortnight of July.

Both wheat and rice crops fertilized with N as 100 and 75 kg N ha^{-1} while both crops received the same 50 kg P_2O_5 ha^{-1} and 25 kg K_2O ha^{-1}, irrespective of the applied treatments. The whole amount of P_2O_5 and K_2O, and 33 per cent of N was applied as basal at the time of seeding with a seed-cum-fertilizer drill and the remaining amount of N was applied in two equal splits using urea. During the rice cycle, 25 kg ZnSO4 ha^{-1} was applied in alternate years. Plant protection measures were used in the event of insect and disease attacks as per the package and practices for different crops developed by SKUAST-Jammu. The weed control under different treatments was conducted as per the Table 1.

2.4. Collection and Preparation of the Soil Samples

Soil sampling was performed at two depths (0–7.5 cm and 7.5–15 cm) after the harvest of wheat at the conclusion of the fourth year, i.e., year 2019–2020, by using the auger at four random locations from each treatment plot. For the assessment of different soil properties, air-dried soil samples were pounded in a wooden pestle and mortar and passed through a 2-mm sieve. For the assaying of enzyme activities and MBC, fresh soil samples were used and stored in a refrigerator at 4 °C for further investigation.

2.5. Fractions of Carbon

Soil organic carbon was assessed by wet digestion as per the Walkley–Black method [27]. The concentration of permanganate oxidizable carbon ($KMnO_4$-C) was determined according to Blair et al. [28], with some modifications proposed by Vieira et al. [29]; the soil was shaken for 1 h with 0.060 M $KMnO_4$ and then centrifuged for 1 h at 2500 rpm. After dilution, the absorbance was measured at 565 nm. A chloroform fumigation extraction technique [30] was employed to determine microbial biomass carbon (MBC). For assessment of MBC, one set of 10-g fresh soil samples was fumigated for 24 h with chloroform (ethanol-free), whereas the other samples were not fumigated. Both fumigated and non-fumigated soils were extracted with 0.5 M K_2SO_4 by shaking for 30 min. For the measurement of particulate organic carbon (POC), soil samples were mixed with a solution of sodium hexametaphosphate (5 g L^{-1}) and shaken at 90 r min^{-1} for 18 h. The dispersed soil solution was wet sieved through a 0.053 mm sieve, and the remaining sample on the sieve was oven dried at 60 °C for 48 h before being tested for POC concentration [18]. Water soluble organic carbon (WSOC) was extracted from 10 g of soil at 25 °C in a 1:5 soil-to-water ratio [31]. The extract was centrifuged for 10 min at 4500 RPM and filtered. The filtrate was treated with $K_2Cr_2O_7$ followed by titration with ferrous ammonium sulphate [18]. Total organic carbon (TOC) was assessed using the dry combustion method, in which a 10-g soil sample was oven dried in an oven at 105 °C for 24 h, weighed, then dry combusted in a muffle furnace at 450 °C for 4 h, with the weight loss considered as carbon loss [32].

2.6. Carbon Pools Based on Oxidizability

Chan et al. [33] modified the Walkley and Black [27] method and separated the TOC into four fractions based on decreasing oxidizability. The details of these fractions are given below:

- Very labile C (Pool I): SOC oxidizable under 12.0 N sulfuric acid;
- Labile C (Pool II): The difference in SOC extracted between 18.0 and 12.0 N sulfuric acid;
- Less labile C (Pool III): The difference in SOC extracted between 24.0 and 18.0 N sulfuric acid;
- Non-Labile or recalcitrant C (Pool IV): Residual organic C after reaction with 24.0 N sulfuric acid when compared with total organic carbon.

2.7. Carbon Management Index (CMI)

The carbon management index was calculated as per procedures given by Blair et al. [28]; in the first step, the lability of C was calculated as per Equation (1)

$$\text{Lability of C(L)} = \frac{\text{C in fraction oxidized by KMnO}_4\left(\text{mg labile Cg}^{-1}\text{soil}\right)}{\text{C remaining unoxidized by KMnO}_4\left(\text{mg nonlabile Cg}^{-1}\text{soil}\right)} = \frac{\text{LBC (Labile C)}}{\text{NLC (Non-labile C)}} \quad (1)$$

The second step is to calculate the lability index and carbon pool index, which were calculated as per Equations (2) and (3):

$$\text{Lability Index (LI)} = \frac{\text{Lability of C in sample soil}}{\text{Lability of C in reference soil}} \quad (2)$$

$$\text{Carbon Pool Index (CPI)} = \frac{\text{Lability of C in sample soil}}{\text{Lability of C in reference soil}} \quad (3)$$

The final step was the calculation of the carbon management index as per Equation (4):

$$\text{Carbon management index (CMI)} = \text{CPI} \times \text{LI} \times 100 \quad (4)$$

The CT (transplanted rice) followed by wheat sown by Conventional tillage without green gram (CTR-CTW) will be used as the reference. The labile C is the portion of SOC oxidized by 333 mM $KMnO_4$ [28].

2.8. Carbon Stock

Carbon stock was calculated as per the equation [34]:

$$\text{SOC stock (Mg ha}^{-1}\text{) = SOC concentration (g kg}^{-1}\text{)} \times \text{soil depth (m)} \times \text{Bulk density (Mg m}^{-3}\text{)} \times 10$$

The soil organic carbon stock was calculated in both layers separately and summation was performed for SOC stock for the 0–30 cm soil layer [34].

2.9. Enzyme Activity

The dehydrogenase activity estimation was based on the principle of triphenyl formazan production from triphenyl tetrazolium chloride, which acts as a hydrogen atoms acceptor [35]. For DHA estimation, 3 percent *w*/*v* 2, 3, 5 triphenyl tetrazolium chloride was added to 1 gm soil followed by the addition of 1-percent glucose solution. After 24 h of incubation at 30 °C temperature, methanol was added and tubes were hand shaken for one minute. The color intensity developed was measured spectrophotometrically at 485 nm and DHA activity was expressed in terms of µg TPFg^{-1} soil 24 h^{-1}. Alkaline phosphatase activity assessment was conducted spectrophotometrically [36] by using modified universal buffer (MUB), toluene, and p-nitrophenyl phosphate (0.025 M). The intensity of yellow color was measured at a 440-nm wavelength (blue filter). The activity of AP was expressed in terms of µg p-nitrophenol released g^{-1} soil h^{-1}.

2.10. Soil Quality Index

For the calculation of the soil quality index, the first step was to define the goal for the soil quality index. Our goal for soil quality indexing was to evaluate the impact of different CA and weed management practices on the overall quality of the soil. The second important step was the selection of a minimum data set (MDS). For MDS parameters, soil parameters with substantial treatment differences were chosen [37] through factor analysis by performing the principal component analysis (PCA). The PCs with high eigenvalues and variables within the PCs with high eigenvalues were considered to characterize the system better. Hence, only PCs with eigenvalues greater than [38], as well as those that explained at least 5% of the variation in the data [39], were included. After the PC selection, the variables with high factor loading from each selected variable were shortlisted. If more than one variable from PC was having high factor loading, then multivariate correlation analysis was performed among variables. The variable with the highest correlation coefficient sum was selected from each shortlisted PC and other parameters were eliminated from the minimum dataset [37]. In the current study, PC1 and PC2 were selected, and out of these PCs, DHA and Very labile C were retained as MDS for soil quality indexing. The third step was to score the indicators. A linear scoring technique was employed to convert each observation of each MDS indicator for this purpose [37]. The indicator was scored as good or bad depending on soil function. For the soil quality indicator, 'more is better'; each observation was divided by the highest observed value, resulting in a score of 1 for the highest value. For the 'less is better' indicator, the lowest observed value (in the numerator) was divided by each observation (in the denominator), yielding a score of 1 [39]. The last step for calculation of the soil quality index was the Integration of indicator score to give *SQI* and is given in Equation (5)

$$SQI = \sum_{i=1}^{n} w_i s_i \quad (5)$$

where S_i is the score for the subscripted variable and W_i is the weighing factor derived from the PCA

W_i was determined by dividing the variance explained by each PC (%) by the total variance of the PCs with eigenvectors greater than one. This proportion, divided by the total percentage of variance explained by all PCs with eigenvectors greater than one, supplied the weighted factor for variables selected under a certain PC. Higher index values were assumed to indicate better soil quality or improved soil function performance. In addition, the percentage contribution of each final key indicator was determined.

2.11. Statistical Analysis

All the data sets were analyzed by using analysis of variance (ANOVA) for factorial randomized block design (Factorial RBD) and the treatment means were separated by DMRT (Duncan Multiple Range Test) at $p < 0.05$ level of significance using Ggplot 2 package of R software Version 3.4.3 [40]. The graphical representation of various data was performed using Microsoft Excel. Principal component analysis (PCA) followed by multivariate correlation analysis was used to select the minimum data set (MDS) to avoid data redundancy by using SPSS 16.0 [37].

3. Results

3.1. Soil Organic Carbon (SOC)

The SOC content in the surface soil layer (0–7.5 cm) was significantly higher under full CA treatment; it was 30.6, 23.5, and 20.6 percent higher than conventional agriculture (T1), partial CA1, and partial CA2 practices, respectively (Table 2). In the second soil layer (7.5–15 cm), the adoption of CA resulted in significantly higher SOC content than partial CA and conventional agriculture treatments; however, SOC content under different WM practices was non-significant.

Table 2. Total Organic carbon (TOC), Carbon Management Index (CMI), Walkley and black carbon (SOC), and SOC stock as affected by different CA and WM practices under the rice–wheat cropping system.

Treatments		SOC (g kg^{-1})		TOC (g kg^{-1})		CMI		SOC Stocks (Mg C ha^{-1})	
WM	**CA**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**
Herbicide	Conventional Agriculture	4.59 ± 0.17 c	2.86 ± 0.07 b	1.12 ± 0.02 ab	0.89 ± 0.01 a	100.0 ± 0 d	100.0 ± 0 a	5 ± 0.2 b	3.59 ± 0.1 b
	Partial CA1	4.97 ± 0.12 bc	3.09 ± 0.08 b	1.12 ± 0.02 ab	0.86 ± 0.02 a	103.4 ± 0.14 cd	109.8 ± 4.6 a	5.62 ± 0.18 b	3.73 ± 0.11 b
	Partial CA2	5.1 ± 0.13 bc	3.17 ± 0.08 b	1.08 ± 0.01 b	0.88 ± 0.03 a	108.9 ± 1.77 bc	115.7 ± 3 a	5.67 ± 0.18 b	3.87 ± 0.08 b
	Partial CA3	5.85 ± 0.14 ab	3.64 ± 0.09 a	1.18 ± 0.01 a	0.89 ± 0.02 a	113.9 ± 1.27 b	111.1 ± 5.1 a	6.91 ± 0.13 a	4.41 ± 0.11 a
	Full CA	6.38 ± 0.23 a	3.97 ± 0.09 a	1.15 ± 0.02 a	0.93 ± 0.01 a	123.7 ± 0.92 a	119.8 ± 3.73 a	7.21 ± 0.32 a	4.71 ± 0.09 a
IWM	Conventional Agriculture	4.74 ± 0.17 c	2.94 ± 0.07 b	1.17 ± 0.03 a	0.72 ± 0.11 b	92.9 ± 1.59 c	106.7 ± 0.23 a	5.23 ± 0.21 b	3.68 ± 0.09 b
	Partial CA1	4.98 ± 0.12 c	3.09 ± 0.08 b	1.11 ± 0.02 b	0.85 ± 0.04 ab	105.5 ± 0.15 b	109.7 ± 0.19 a	5.59 ± 0.18 b	3.83 ± 0.12 b
	Partial CA2	5.12 ± 0.13 bc	3.18 ± 0.08 b	1.04 ± 0 c	0.87 ± 0.02 ab	106.2 ± 2.1 b	108.6 ± 3.56 a	5.77 ± 0.11 b	3.89 ± 0.13 b
	Partial CA3	5.98 ± 0.15 ab	3.72 ± 0.09 a	1.15 ± 0.02 ab	0.93 ± 0.02 a	115.4 ± 2.72 a	109.0 ± 1.58 a	7 ± 0.15 a	4.51 ± 0.11 a
	Full CA	6.44 ± 0.21 a	4 ± 0.1 a	1.17 ± 0.01 ab	0.89 ± 0.01 a	121.7 ± 3.02 a	113.5 ± 6.58 a	7.18 ± 0.15 a	4.69 ± 0.12 a
Weedy Check	Conventional Agriculture	4.78 ± 0.23 b	2.98 ± 0.07 b	1.14 ± 0.02 bc	0.91 ± 0.01 a	89.7 ± 2.14 c	89.3 ± 4.33 b	5.14 ± 0.24 b	3.71 ± 0.08 b
	Partial CA1	4.97 ± 0.12 b	3.09 ± 0.08 b	1.11 ± 0 c	0.87 ± 0.01 a	102.9 ± 1.66 b	104.7 ± 2.41 ab	5.62 ± 0.17 b	3.76 ± 0.1 b
	Partial CA2	5.07 ± 0.12 b	3.15 ± 0.08 b	1.2 ± 0.01 ab	0.92 ± 0.01 a	103.9 ± 0.16 b	110.6 ± 4.08 a	5.64 ± 0.18 b	3.9 ± 0.07 b
	Partial CA3	6.22 ± 0.21 a	3.87 ± 0.09 a	1.21 ± 0.01 a	0.89 ± 0.02 a	118.4 ± 1.58 a	118.2 ± 3.86 a	7.05 ± 0.1 a	4.67 ± 0.12 a
	Full CA	6.51 ± 0.28 a	4.05 ± 0.1 a	1.15 ± 0.01 abc	0.89 ± 0.03 a	125.6 ± 0.79 a	121.9 ± 5.63 a	7.21 ± 0.21 a	4.67 ± 0.14 a

Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, DMRT test) n.

3.2. Fractions of Carbon

All the labile fractions of carbon ($KMnO_4$-C, MBC, WSOC, and POC) were influenced significantly by the adoption of CA practices in the surface layer (0–7.5 cm) after four crop cycles. In the surface soil layer (0–7.5 cm), the highest $KMnO_4$-C content was reported under full CA, which was 46.3%, 24.2%, 23.4%, and 7.7% higher than conventional agriculture (T1) and partial CA (pCA1, pCA2, and pCA2), respectively. Other labile C fractions under study such as MBC, WSOC, and POC concentration in the surface layer was affected by different CA practices. Adoption of full CA resulted in 52.3%, 152.4%, and 15.6% higher MBC, WSOC, and POC, respectively, compared to conventional agriculture. In the second layer, all labile fractions except POC were affected by CA treatments (Table 3). Among the weed management practices, only $KMnO_4$-C and MBC in the surface layer were affected by WM practices, whereas other labile fractions were not affected by WM practices (Figure 2).

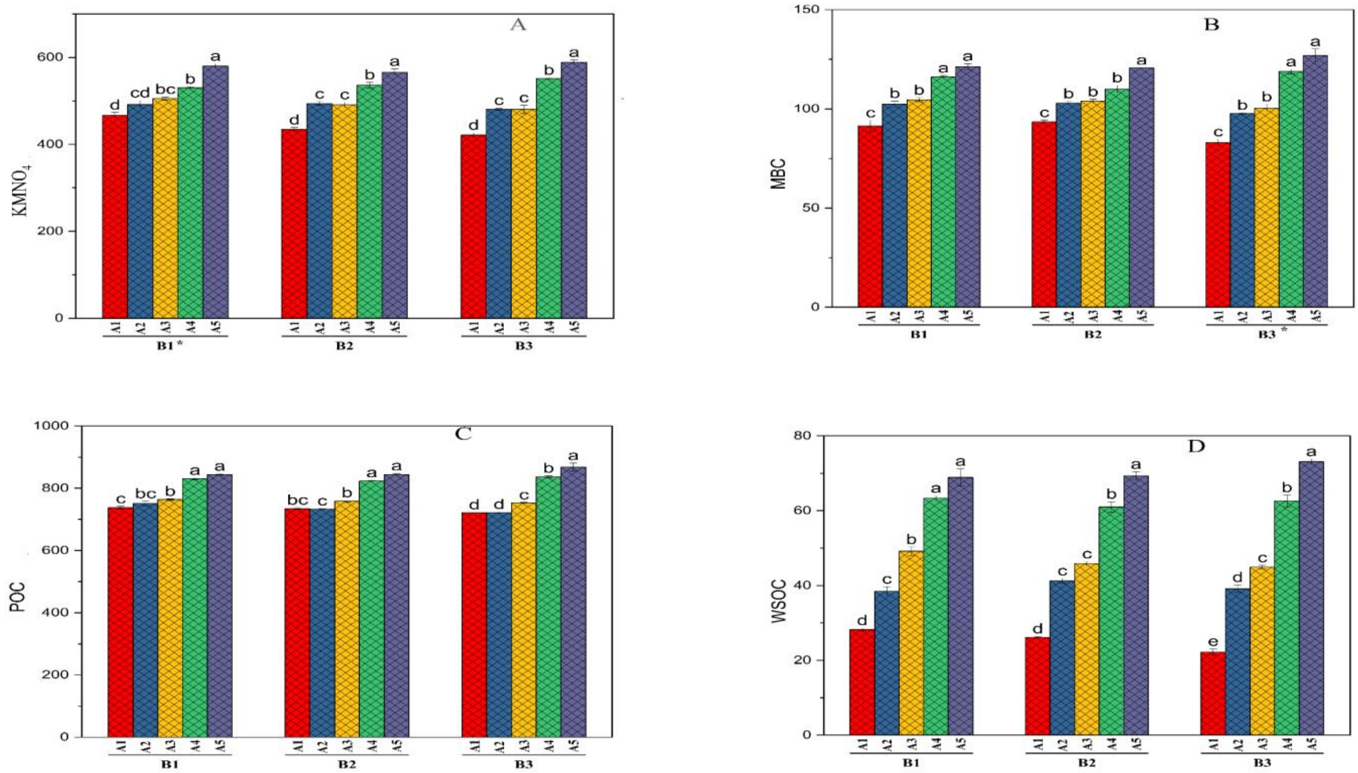

Figure 2. Labile fractions of soil organic carbon (mg kg^{-1}) as affected by different CA and weed management practices in surface soil layer (0–7.5 cm). (**A**) KMnO4-C, (**B**) MBC, (**C**) POC, and (**D**) WSOC. CA treatments: A1: CTR-CTW, A2: CTR-ZTW-ZTG, A3: CTDSR-CTW-ZTG, A4: ZTDSR-ZTW+R-ZTG, A5: ZTDSR+R-ZTW+R+ZTG. WM Treatments: B1: Herbicide, B2: Integrated weed management, B3: Weedy check Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, DMRT test), Standard error denoted by error bar. * Denotes the significantly ($p \leq 0.05$) higher value of $KMnO_4$–C in herbicide treatment and higher MBC in weedy check treatment under weed management practices.

The TOC content of all CA practices was statistically on par with each other across all the depths at the end of the fourth year of continuous CA. Different weed management practices did not influence the particulate organic carbon and total soil organic carbon in both soil layers under study (Table 2).

Table 3. Labile fractions of carbon, i.e., water soluble organic carbon (WSOC), permanganate oxidizable organic carbon ($KMnO_4$-C), microbial biomass carbon (MBC), and particulate organic carbon (POC) as affected by different CA and WM practices under the rice–wheat cropping system.

Treatments		WSOC (mg kg^{-1})		$KMnO_4$-C (mg kg^{-1})		POC (mg kg^{-1})		MBC (mg kg^{-1})	
WM	**CA**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**
Herbicide	Conventional Agriculture	28.24 ± 0.38 d	23.04 ± 0.7 d	466.9 ± 5.9 d	270.9 ± 9.08 b	737.6 ± 4.52 c	482.1 ± 2.8 c	91.42 ± 2.79 c	87.26 ± 0.49 c
	Partial CA1	38.46 ± 1.25 c	32.73 ± 0.54 c	491.7 ± 9.2 cd	287.9 ± 4.88 ab	750.9 ± 7.38 bc	507.3 ± 3.22 b	102.44 ± 1.56 b	87.41 ± 1.05 c
	Partial CA2	49.17 ± 1.1 b	38.96 ± 0.66 b	505.1 ± 3.88 bc	305.4 ± 1.84 ab	763.4 ± 2.41 b	518.9 ± 4.41 b	104.66 ± 1 b	89.03 ± 0.59 bc
	Partial CA3	63.34 ± 0.67 a	58.06 ± 0.88 a	530.2 ± 2.32 b	290.9 ± 6.37 ab	830.5 ± 3.1 a	544.2 ± 1.9 a	116.12 ± 0.7 a	95.77 ± 1.85 b
	Full CA	68.9 ± 2.31 a	58.94 ± 0.79 a	580.3 ± 5.1 a	313.8 ± 2.18 a	844.6 ± 2.47 a	553.1 ± 5.36 a	121.32 ± 1.45 a	105.48 ± 2.27 a
IWM	Conventional Agriculture	26.14 ± 0.28 d	23.52 ± 0.58 e	435.0 ± 3.46 d	272.2 ± 10.11 a	735.3 ± 2.42 bc	481.9 ± 2.3 c	93.36 ± 0.98 c	87.58 ± 1.4 c
	Partial CA1	41.26 ± 0.62 c	33.24 ± 1.12 d	494.0 ± 4.41 c	289.1 ± 5.83 a	732.4 ± 2.51 c	509.6 ± 5.2 b	102.91 ± 0.95 b	87.94 ± 1.74 c
	Partial CA2	45.89 ± 0.53 c	39.3 ± 0.57 c	491.2 ± 5.67 c	287.3 ± 2.98 a	758.1 ± 3.34 b	522.5 ± 6.36 b	103.86 ± 0.94 b	93.04 ± 0.58 bc
	Partial CA3	61.03 ± 1.39 b	58.64 ± 0.67 b	535.8 ± 6.47 b	286.9 ± 2.62 a	823.4 ± 2.44 a	548.0 ± 4.57 a	109.97 ± 1.97 b	101.04 ± 1.34 ab
	Full CA	69.3 ± 1.1 a	64.13 ± 0.88 a	566.0 ± 7.37 a	303.1 ± 11.32 a	844.7 ± 3.19 a	556.5 ± 2.68 a	120.65 ± 0.09 a	106.66 ± 1.67 a
Weedy Check	Conventional Agriculture	22.2 ± 0.86 e	21.43 ± 0.64 d	421.0 ± 5.27 d	233.6 ± 17.24 c	721.6 ± 1.08 d	481.3 ± 9.53 c	82.98 ± 1.68 c	82.01 ± 1.18 b
	Partial CA1	39.14 ± 1.02 d	30.9 ± 0.53 c	481.1 ± 2.52 c	275.3 ± 0.5 b	721.6 ± 2.56 d	499.2 ± 3.87 bc	97.59 ± 0.45 b	84.7 ± 2.05 b
	Partial CA2	44.92 ± 0.48 c	37.01 ± 0.67 b	480.2 ± 9.52 c	293.8 ± 4.63 ab	752.7 ± 1.89 c	518.0 ± 0.55 b	100.34 ± 1.93 b	85.95 ± 2.58 b
	Partial CA3	62.63 ± 1.54 b	60.55 ± 0.97 a	551.2 ± 2 b	306.1 ± 4.49 ab	836.7 ± 3.58 b	557.3 ± 5.96 a	118.82 ± 1.16 a	102.64 ± 1.67 a
	Full CA	73.08 ± 0.72 a	63.35 ± 0.4 a	588.5 ± 5.6 a	314.5 ± 7.96 a	867.8 ± 13.16 a	567.2 ± 1.56 a	126.85 ± 3.35 a	108.62 ± 0.88 a

Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, DMRT test).

3.3. Carbon Pools Based on Oxidizability

The quantification of labile and recalcitrant SOC pools as altered by tillage and straw management techniques was addressed. In the 0–7.5-cm soil layer, active pools of SOC (very labile and labile C), CA resulted in higher active pools of SOC than conventional agriculture plots, whereas passive pools remain unchanged with management (Table 4). Full CA resulted in 54.3%, 45.1%, 41.4%, and 8.6% higher very labile carbon (VLC) than that over conventional agriculture, partial CA1, partial CA2, and partial CA3, respectively. In the subsurface layer (7.5–15 cm) only VLC was affected by CA treatments. Similar trends were observed in labile carbon. The passive pools of carbon (less labile and recalcitrant pool) were not affected by adoption of CA practices (Table 4 and Figure 3). The different pools of SOC based on oxidizability, were similar under all the WM practices across both depths under study.

Table 4. Soil organic carbon pools (g kg^{-1}) based on oxidizability as affected by different CA and WM practices under the rice–wheat cropping system.

Treatments		**Very Labile Pool**		**Labile Pool**		**Less Labile Pool**		**Non-Labile Pool**	
WM	**CA**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**	**0–7.5 cm**	**7.5–15 cm**
Herbicide	Conventional Agriculture	2.12 ± 0.04 b	1.31 ± 0.05 b	1.64 ± 0.04 c	1.07 ± 0.04 b	0.84 ± 0.04 a	0.47 ± 0.04 a	4.64 ± 0.52 a	2.84 ± 0.22 a
	Partial CA1	2.18 ± 0.1 b	1.44 ± 0.04 b	1.82 ± 0.05 bc	1.19 ± 0.04 ab	0.85 ± 0.04 a	0.49 ± 0.03 a	4.92 ± 0.56 a	1.73 ± 0.12 b
	Partial CA2	2.4 ± 0.1 b	1.5 ± 0.05 b	1.85 ± 0.05 bc	1.2 ± 0.04 ab	0.86 ± 0.04 a	0.48 ± 0.04 a	4.94 ± 0.56 a	1.74 ± 0.11 b
	Partial CA3	2.97 ± 0.03 a	1.85 ± 0.06 a	1.97 ± 0.05 ab	1.29 ± 0.04 a	0.92 ± 0.06 a	0.52 ± 0.03 a	5.65 ± 0.66 a	1.8 ± 0.12 b
	Full CA	3.33 ± 0.13 a	2.04 ± 0.05 a	2.08 ± 0.05 a	1.36 ± 0.04 a	0.98 ± 0.05 a	0.56 ± 0.02 a	6.01 ± 0.7 a	1.83 ± 0.12 b
IWM	Conventional Agriculture	2.23 ± 0.06 c	1.38 ± 0.05 b	1.69 ± 0.04 c	1.1 ± 0.04 b	0.82 ± 0.04 a	0.47 ± 0.03 a	4.69 ± 0.6 a	2.91 ± 0.23 a
	Partial CA1	2.36 ± 0.05 c	1.45 ± 0.04 b	1.8 ± 0.04 bc	1.17 ± 0.04 ab	0.85 ± 0.04 a	0.46 ± 0.02 a	4.94 ± 0.56 a	1.71 ± 0.12 b
	Partial CA2	2.45 ± 0.04 c	1.52 ± 0.05 b	1.81 ± 0.05 bc	1.18 ± 0.04 ab	0.88 ± 0.06 a	0.5 ± 0.03 a	4.98 ± 0.57 a	1.73 ± 0.11 b
	Partial CA3	2.97 ± 0.09 b	1.92 ± 0.03 a	1.98 ± 0.05 ab	1.29 ± 0.04 a	0.9 ± 0.05 a	0.51 ± 0.03 a	5.69 ± 0.66 a	1.79 ± 0.13 b
	Full CA	3.39 ± 0.1 a	2.11 ± 0.02 a	2.06 ± 0.05 a	1.35 ± 0.04 a	0.98 ± 0.05 a	0.56 ± 0.02 a	6 ± 0.7 a	1.82 ± 0.14 b
Weedy Check	Conventional Agriculture	2.25 ± 0.12 b	1.4 ± 0.04 b	1.71 ± 0.04 c	1.12 ± 0.04 b	0.86 ± 0.05 a	0.48 ± 0.03 a	4.79 ± 0.54 a	1.7 ± 0.13 a
	Partial CA1	2.36 ± 0.04 b	1.46 ± 0.05 b	1.76 ± 0.04 c	1.15 ± 0.04 b	0.87 ± 0.03 a	0.5 ± 0.03 a	4.91 ± 0.56 a	1.7 ± 0.12 a
	Partial CA2	2.35 ± 0.09 b	1.45 ± 0.04 b	1.85 ± 0.05 bc	1.2 ± 0.04 ab	0.89 ± 0.05 a	0.51 ± 0.03 a	4.97 ± 0.57 a	1.74 ± 0.11 a
	Partial CA3	3.26 ± 0.05 a	2.03 ± 0.04 a	2.06 ± 0.05 ab	1.34 ± 0.04 a	0.92 ± 0.05 a	0.53 ± 0.03 a	5.82 ± 0.68 a	1.82 ± 0.15 a
	Full CA	3.43 ± 0.04 a	2.13 ± 0.07 a	2.13 ± 0.06 a	1.38 ± 0.04 a	0.97 ± 0.05 a	0.55 ± 0.02 a	6.12 ± 0.72 a	1.84 ± 0.12 a

Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, DMRT test).

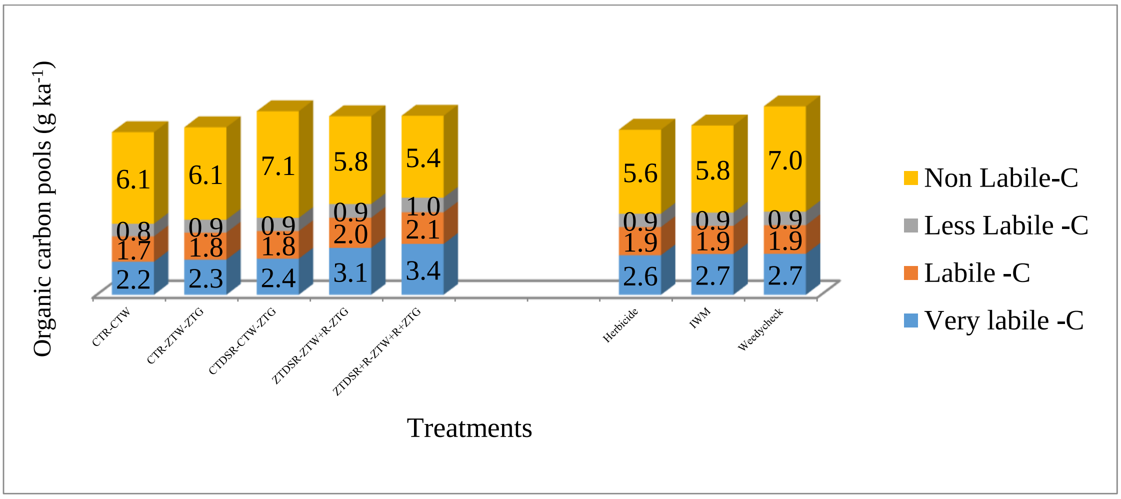

Figure 3. Soil organic carbon pools (g kg^{-1}) based on oxidizability as affected by different CA and WM practices under the rice–wheat cropping system.

3.4. Carbon Management Index (CMI)

Carbon management index (CMI), LI, and CPI under CA practices were all affected significantly by the adoption of different levels of conservation agriculture practices up to 15 cm soil layers. In the surface soil layer, the adoption of full CA resulted in 48.9%, 25.3%, 24.8%, and 8.0% higher CMI than conventional agriculture, pCA1, pCA2, and pCA3, respectively. The integrated weed management resulted in significantly lower CMI than the application of herbicide in the surface layer only (Table 2).

3.5. Enzyme Activities

The dehydrogenase activity owing to different establishment methods was influenced significantly up to the depth of 15 cm. Full CA resulted in 104.3% higher DHA activity than CTR-CTW. The DHA activity was lowest under conventional agriculture (CTR-CTW), 29.7% lower than partial CA1, which, in turn, was on par with partial CA2 (Table 5). Similarly, the full CA practice increased the phosphatase activity by 40.6%, 33.5%, and 30.6% over conventional agriculture practices, partial CA1, and partial CA2, respectively. Among different WM treatments, weedy cheek resulted in 10.6% and 8.9% higher APA over the application of herbicide and integrated weed management. The phosphatase activity in the subsurface layer was on par with all weed management practices after the completion of four crop cycles (Table 5).

Table 5. Dehydrogenase activity (µg TPF g^{-1} soil 24 h^{-1}), alkaline phosphatase activity (µg p-NP g^{-1} h^{-1}), and soil quality index as affected by different conservation agriculture and weed management treatments under the rice–wheat cropping system.

Treatments		Dehydrogenase Activity		Alkaline Phosphate Activity		Soil Quality Index
WM	CA	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm	
Herbicide	Conventional Agriculture	91.17 ± 0.42 d	72.5 ± 1.54 c	168.34 ± 1.67 c	111.67 ± 1.67 bc	0.70 ± 0.005 d
	Partial CA1	113.67 ± 2.29 c	80.48 ± 0.63 bc	175.0 ± 2.89 bc	108.34 ± 1.67 c	0.79 ± 0.009 c
	Partial CA2	115.82 ± 2.13 c	87.52 ± 3.27 b	185.0 ± 2.89 b	115.0 ± 5 bc	0.80 ± 0.011 c
	Partial CA3	128.27 ± 0.87 b	100.19 ± 0.85 a	208.34 ± 1.67 a	130.0 ± 0 ab	0.86 ± 0.024 b
	Full CA	140.71 ± 3.24 a	101.83 ± 1.47 a	216.67 ± 6.67 a	145.0 ± 2.89 a	0.95 ± 0.012 a
IWM	Conventional Agriculture	87.58 ± 0.72 d	72.03 ± 1.03 c	163.67 ± 1.86 b	116.67 ± 4.41 b	0.65 ± 0.021 d
	Partial CA1	111.75 ± 0.64 c	82.12 ± 0.82 bc	175.0 ± 2.89 b	118.34 ± 1.67 b	0.77 ± 0.014 c
	Partial CA2	111.27 ± 1.25 c	91.98 ± 4.48 ab	178.34 ± 1.67 b	118.34 ± 1.67 b	0.78 ± 0.014 c
	Partial CA3	128.75 ± 1.46 b	100.43 ± 0.41 a	221.67 ± 1.67 a	141.67 ± 1.67 a	0.86 ± 0.002 b
	Full CA	141.43 ± 1.1 a	99.96 ± 0.24 a	230.0 ± 5.78 a	141.67 ± 1.67 a	0.92 ± 0.022 ab
Weedy Check	Conventional Agriculture	86.62 ± 1.05 d	72.97 ± 0 b	163.34 ± 3.34 b	110.0 ± 5.78 b	0.65 ± 0.003 d
	Partial CA1	106.73 ± 0.87 c	83.06 ± 2.45 b	171.67 ± 1.67 b	110.0 ± 5.78 b	0.76 ± 0.002 c
	Partial CA2	111.04 ± 1.34 c	95.03 ± 3.27 a	170.0 ± 0.2 b	113.34 ± 1.67 b	0.77 ± 0.005 c
	Partial CA3	136.4 ± 1.81 b	101.13 ± 0.41 a	235.0 ± 2.89 a	146.67 ± 4.41 a	0.92 ± 0.014 ab
	Full CA	147.65 ± 0.87 a	102.77 ± 2.49 a	250.0 ± 0.24 a	141.67 ± 7.27 a	0.97 ± 0.003 a

Means of column followed by the same letters within each column not statistically different ($p \leq 0.05$, DMRT test).

3.6. SOC Stock

The oxidizable carbon stock values obtained after the completion of the fourth cropping cycle were significantly influenced under different establishment methods up to the depth of 15 cm (Table 2). In the 0–7.5 cm soil layer, the highest SOC stock sequestered under full CA treatment (7.19 Mg C ha^{-1}) was on par with partial CA3 (6.98 Mg C ha^{-1}) and higher by 40.6, 28.4, and 26.5 percent over conventional agriculture treatments and partial CA1 and partial CA2 treatments, respectively. Different CA treatments had a similar pattern of considerable impact on the SOC stock in the lower soil layer (7.5–15 cm). The largest carbon stock (4.69 Mg C ha^{-1}) was found in full CA treatment, which was 28.3%, 24.3%, and 20.7% greater than traditional agriculture and the partial CA1 and CA2 treatments, respectively. The whole soil profile (0–15 cm) SOC stock was 26.2%, 18.1%, and 18.4% higher under full CA than that of conventional agriculture and partial CA1 and partial CA2, respectively.

3.7. Soil Quality Index

The scree plot was used to depict the link between the eigenvalue and PC. A drop in eigenvalue is observed in direct proportion to an increase in PC; after PC4, the eigenvalue dropped sharply from 9.76 to 1.09 when the PC number increased from PC1 to PC2 (Figure 4). Two PCs that had eigenvalues larger than 1 were retrieved, and these PCs can account for 83.49% of all variances (Table 6). The retained PCs of the data under various CA and weed management treatments were then subjected to varimax rotation (Figure 5), resulting in the distribution of each PC's variance and maximizing the link between interdependent variables. Dehydrogenase activity with positive factor loading (0.98), microbial biomass carbon, MBC, $KMnO_4$-C, CMI, and labile carbon pool are among the variables that PC1 showed had an eigenvalue of 9.76 and explained roughly 75.08 percent of the variance. Only one loading, TOC with a positive factor loading, was included in PC2, which explained approximately 8.4% of the variance and had an eigenvalue of 1.09 (Table 7). Communities show the relative contribution of each soil characteristic to all the retrieved PCs, indicating the significance of each property. Each soil characteristic has helped to improve the soil quality, which was described in terms of commonalities.

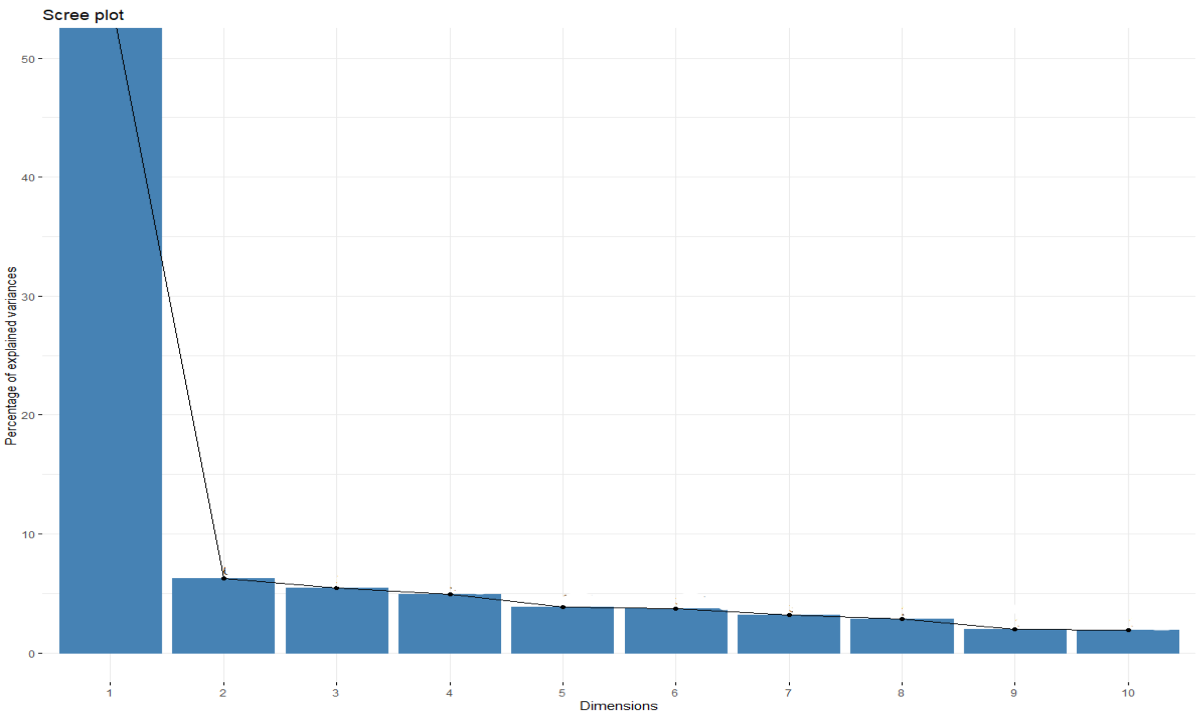

Figure 4. Scree plot showing the relationship between Principal components (PCs) and variance explained.

Table 6. Principle component analysis (PCA) of soil quality indicators under study.

	Component Matrix													
Component	**$KMnO_4C$**	**WSOC**	**POC**	**MBC**	**TOC**	**CMI**	**DHA**	**APA**	**SOC**	**Stock**	**VLC**	**LC**	**LLC**	**RC**
1	0.975	0.831	0.981	0.971	0.819	0.511	0.970	0.878	0.892	0.777	0.888	0.973	0.756	0.668
2	−0.151	0.492	−0.191	0.271	0.793	−0.240	0.163	−0.003	−0.046	−0.075	0.039	−0.092	−0.216	−0.354

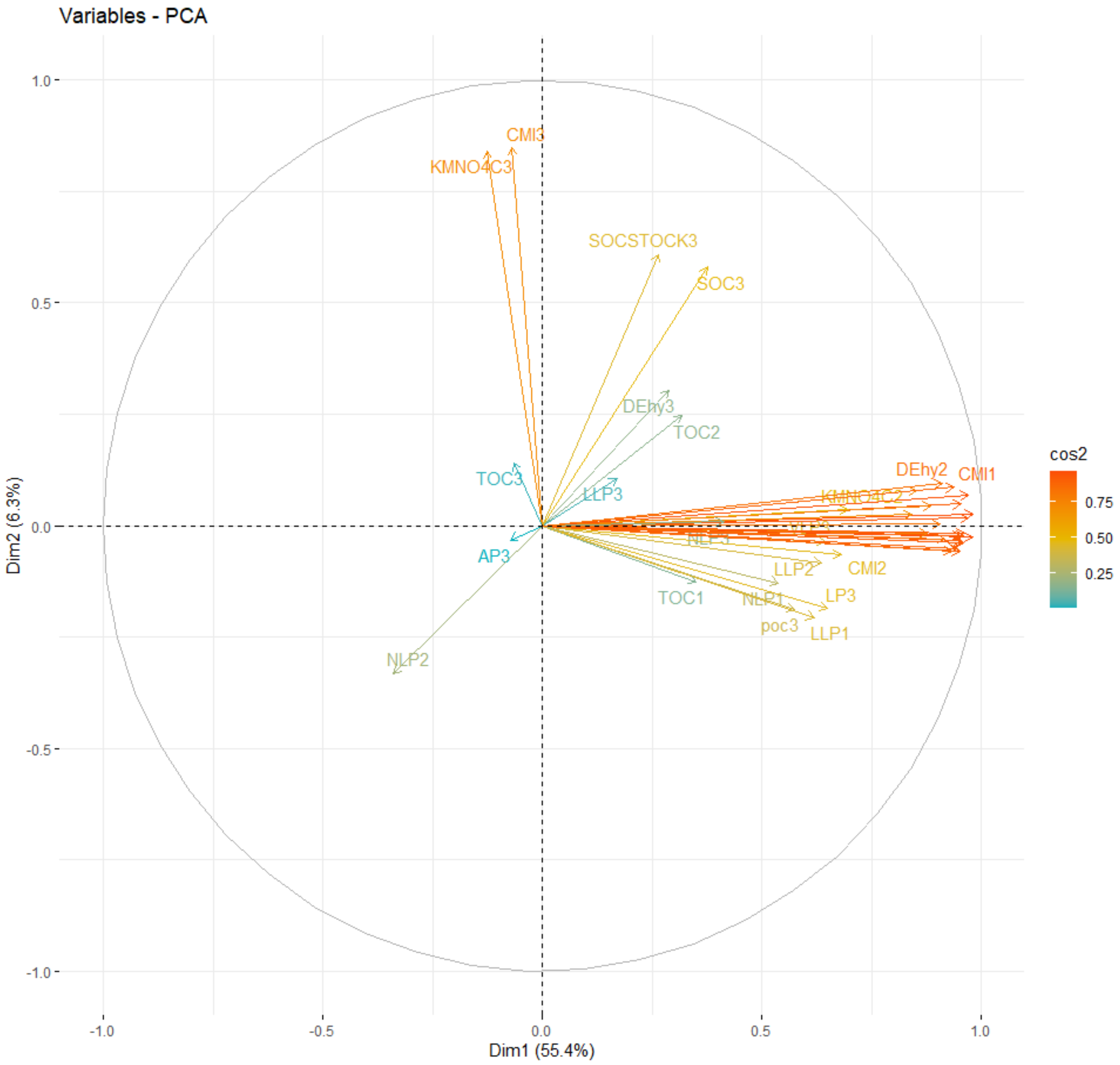

Figure 5. Principal component plot of soil carbon properties and enzyme activities under different conservation agriculture- and weed management-based agricultural practices. $KMnO_4$-C- Permanganate oxidizable carbon, Dehy: Dehydrogenase activity, LLP: Less labile carbon pool, AP: Alkaline phosphatase activity, TOC: Total organic carbon, NLP: non-labile carbon pool, CMI: carbon management index.

Table 7. List of selected parameters for minimum data set (MDS) as affected by conservation agriculture and weed management treatments after 4 years of continuous crop cycles under the rice–wheat cropping system.

PC Number	Eigenvalue	% Variance	Cumulative Percent	Weight of Each PC	Indicators Selected for SQI
PC1	9.761	75.082	75.082	0.89	$KMnO_4$-C
PC2	1.094	8.414	83.496	0.10	TOC

3.8. Selection of Minimum Data Set Attributes (MDS)

Table 8 shows the correlation matrix for the highly weighted factors in PC1. The variables with the greatest correlation total were deemed to best reflect the group. Permanganate oxidizable carbon ($KMnO_4$-C) was chosen for the MDS as the variable with the greatest correlation sum (4.86) among the five variables in PC1. Dehydrogenase activity (4.85), MBC (4.77), CMI (4.77), and labile carbon pool (4.77) were eliminated from PC1 because the total of correlation was lower than KMnO4-C. TOC was retained in PC2 since it was the only parameter with a factor loading larger than 0.5.

Table 8. Correlation matrix of different parameters shortlisted in PC1 for MDS.

Parameter	MBC	$KMnO_4$-C	CMI	Dehydrogenase	Labile-C
MBC	1.00	0.96	0.91	0.96	0.94
$KMnO_4$-C	0.96	1.00	0.99	0.97	0.95
CMI	0.91	0.99	1.00	0.95	0.92
Dehydrogenase	0.96	0.97	0.95	1.00	0.97
Labile –C	0.94	0.95	0.92	0.97	1.00
Total	4.77	4.86	4.77	4.85	4.77

These selected soil attributes, viz., $KMnO_4$-C and TOC, indicate that these parameters play a significant role in improving the sustainability of land usage. The remaining soil parameters were either less factor loaded or poorly connected with one another; therefore, they were eliminated.

3.9. Scoring of Indicators

Using a linear scoring approach, selected indicators in MDS were scored into dimensionless values ranging from 0 to 1. Depending on whether a greater number was regarded "good" or "bad" in terms of soil function, indicators were evaluated in ascending or descending order. For the KMnO4-C and TOC (higher is better) indicators, each value was divided by the highest value, giving the highest value a score of 1.

3.10. Soil Quality Index (SQI)

In order to generate the final index value for soil quality under different management practices, the indicator score was multiplied by the weighting factor driven from the PCA. Table 8 shows the weight of each PC based on percent variation to total variance, which varied from 0.10 to 0.89 (Table 8). Data revealed that different crop establishment methods and straw management practices significantly affected the soil quality index (Table 5). The descending order of mean SQI as affected by different CA treatments was full CA (0.94) > partial CA3 (0.88) > partial CA2 (0.78) partial CA1 (0.77) > conventional agriculture (0.67). The adoption of CA practices resulted in an improvement in the soil quality index over conventional agriculture practices. Among the different indicators of soil quality, the contribution of $KMnO_4$-C was the highest (Figure 6).

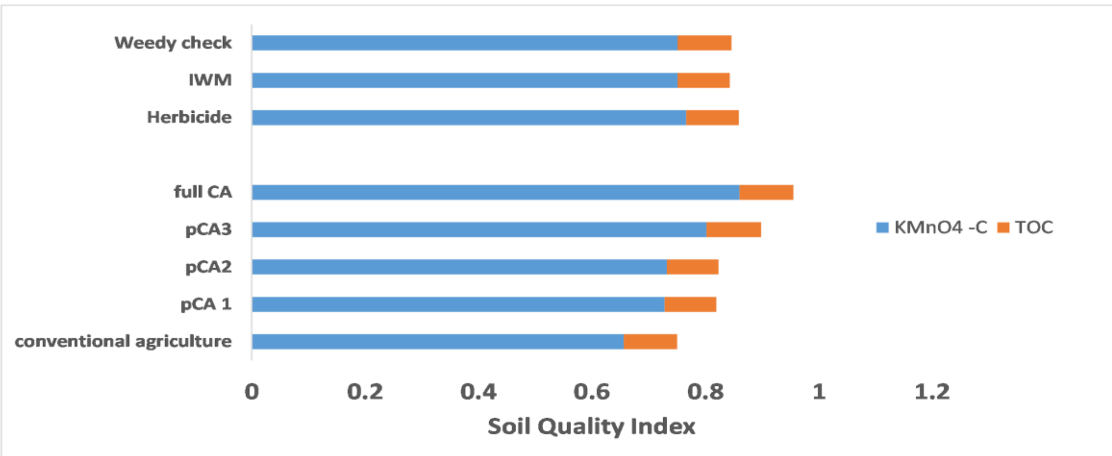

Figure 6. Soil quality index under different conservation agriculture- and weed management-based agricultural practices with individual contribution of each parameter under MDS.

4. Discussion

4.1. Walkley and Black Carbon (SOC)

Reduced tillage intensity under CA led to decreased disturbance of soil aggregates and improved physical protection of SOC inside macroaggregates, leading to an increase in SOC [14]. Secondly, under CA, the addition of fresh organic matter in the form of rice, wheat, or mungbean residues contributed to the development of organic matter in the surface soil [41]. Residue retention could have also improved water retention and kept temperatures in a moderate range, which further slowed the breakdown of SOM (investigations [4,34,42]. Increased stratification of SOC under CA may be caused by mixing surface soil with tillage tools during seed-bed preparation and increasing root density [4]. The results obtained in our current investigations were in accordance with earlier studies conducted by some researchers across the globe [4,12,34,42,43].

4.2. Permanganate Oxidizable Carbon (KMnO$_4$-C)

The KMnO4-C is a labile C fraction and considered as an early indicator of long-term SOC changes caused by crop management practices [44]. Fresh organic matter input in the form of rice, wheat, or mungbean residues retained on the soil surface served a crucial role in organic matter build-up in the surface soil [41], thereby resulting in a higher concentration of comparatively more labile SOC in the upper soil layer under CA [45,46]. In no-tillage systems, improved soil microenvironment, including soil temperature, soil aggregation, porosity, soil moisture, etc., had been associated with an increase in KMnO$_4$-C. This has further raised the activities of soil microbes and enzymes [46]. The prior research also corroborated the current investigation's finding that CA treatments produced larger concentrations of KMnO$_4$-C than traditional agricultural treatments [2,12,47–49]. In contrast to the aforementioned results, Guo et al. [17] and Li et al. [18] found that the short-term impacts of CA on KMnO$_4$-C concentrations were not substantial.

Among WM practices, herbicide application resulted in a significant reduction in KMC as compared to the weedy check. It might be due to a decline in enzyme activity and less accumulation of root exudates and hormones in the rhizosphere due to the control of weed flora under herbicide application [50]. Mishra et al. [51] revealed that a significant quantity of organic matter is accumulated in weedy check and hand weeded conditions compared to herbicides.

4.3. Microbial Biomass Carbon (MBC)

Crop residue retention under ZT boosted microbial biomass, which, in turn, promoted soil biological activity [52]. The enhanced availability of substrate to support the microbial biomass under CA treatments may account for higher levels of microbial biomass [53]. Frequent tillage under CT breaks down aggregates and exposes protected organic matter to microbial decomposition, thereby increasing the loss of labile C fractions [54]. No-tillage improved soil structure and adjust soil water, heat, gas, and plant nutrient cycles, which supplied the energy to microbe populations for survival. These circumstances could dramatically increase soil microbial populations [55]. Several researchers [2,48,55,56] reported a marked increase in microbial biomass under CA treatments over conventional agriculture treatments.

4.4. Particulate Organic Carbon (POC)

The POC may be regarded as an intermediary between active and passive fractions of SOC that may vary due to different management practices [57]. This intermediate fraction provides substrates for microorganisms and impacts soil aggregation [58]. According to Cambardella and Elliott [57], the reason there is less particle organic matter in tilled soils compared to no-tillage soils is due to a quicker rate of decomposition. The stronger protection of coarse and fine particulate organic matter under zero tillage than under CT might be the cause of the higher percentage of SOC as POC [59]. In CA-based treatments, the combination of crop residues and ZT caused greater particulate organic carbon (POC) generation. Studies cited by several researchers also indicated the substantial improvement of POC under CA procedures [2,60,61].

4.5. Water Soluble Organic Carbon (WSOC)

Water soluble organic carbon (WSOC) is derived from a variety of sources, such as root exudates, plant litter, microbial biomass, and soil humus [62]. The positioning of residues close to the soil surface may be the cause of higher WSOC under CA. High crop yields may promote plant rhizodeposition, which would raise the topsoil's WSOC content [63]. Frequent ploughing and conventional farming exacerbated the loss of labile C components by aggregate disintegration and microbial degradation of protected organic compounds [13]. Soluble organic materials such as protein, starch, and monosaccharides are released into the soil by decaying crop straw [54,64], increasing the soil WSOC concentration under the residue retention. Our result supports other studies that recorded higher WSOC at the upper layers under CA [12,18,65].

4.6. Total Organic Carbon (TOC)

The quantity of carbon bound in organic compounds in the soil is referred to as total organic carbon. Different CA practices had no effect on TOC. Given the huge background of SOC, the fact that TOC evolves slowly and is typically insensitive to short-term management practices is a plausible explanation for similar TOC under all tillage treatments [66]. Due to its slow turnover rate and large soil organic C pool, Wang et al. [67] reported that TOC required a significant amount of time (>5 years) to respond to residue amendments. Several other studies found that long-term adoption of CA enhanced soil TOC content as compared to conventional agriculture [47,68,69].

4.7. Carbon Pools Based on Oxidizability

Due to CA and other management practices, SOC composition and quantity in the soil profile, as well as changed root C dynamics, may be responsible for the greater content of active pools (VLC + LC) of carbon following CA treatments [70]. The macro aggregation is enhanced by the transient binding materials (fungal hyphae), while the bioproducts generated by root exudation and breakdown processes improved clay and silt particle aggregation. As a result, CA approaches may be the reason for higher SOC labile pool concentrations [71]. The larger concentration of active carbon pools in the upper layer was most likely caused by an increased topsoil microbial population in the residue-retained plots [42]. At two depths, crop establishment techniques, straw recycling, and weed control had minimal impact on passive pools of carbon, also known as less liable and non-liable (recalcitrant pool). Although the recalcitrant (non-labile) pool is slowly altered by management practices, it contributes significantly towards SOC stock accumulation [72]. These findings concur with those of Blair et al. [28], who discovered that non-labile carbon pools were mostly indifferent to soil and crop management. According to Majumder et al. [73], the labile pools were vital for crop production because they sustain the soil food web and had a substantial influence on nutrient cycling, which is required to maintain soil quality and productivity.

4.8. Carbon Management Index (CMI)

Blair et al. [28] created the concept of CMI to assess the state and rate of variation in soil carbon of different systems (agricultural and natural systems) based on changes in TOC and easily oxidizable C of soils. According to Li et al. [18], CMI is a useful indicator for soil quality evaluation in different agricultural systems. Higher CMI indicates that the soil could provide more nutrients for crop development [74]. As a result of the adoption of continuous CA, enhanced annual C inputs and the variation in organic matter content, changed the lability of C to an easily oxidized state; hence, plots under CA had higher CMI than those under conventional agriculture [75]. The higher CMI under CA treatments could also be related to the climate and soil type of soil labile organic C [63]. Our results received the support of other studies that recorded higher carbon management index at the surface soil layer under CA [12,18,65,71].

4.9. Enzyme Activities

The DHA, an oxidoreductase enzyme, is considered a vital parameter of soil quality evaluation and a consistent biomarker that reflect changes in total microbial activity due to management practices [76]. Under CA, C supplied through rice, wheat, and mungbean straws to boost microbial activity and biomass, which further enhanced the activities of many enzymes [77]. Soil enzyme activities were reported to be negatively correlated with CT [78] highly correlated with ZT [79]. Relatively higher concentrations of nitrogen, potassium, phosphorus, and micronutrient under CA treatments provided a substrate for the activity of dehydrogenase, thereby improving the DHA activity in the soil [15,80]. The results of the present study showed consistency with the previous findings as documented by different researchers [15,48,49,56,81].

Different degrees of CA (straw retention treatments) significantly increased the APA, which improved substrate availability and provided a more favorable environment for microbial biomass than treatments that removed the straw [80]. Increased microbial activity, especially MBC, was linked to higher alkaline phosphatase activity as a result of the release of organic compounds, which also had a beneficial "rhizosphere impact" [78] on the secretion of enzymes in soil. Our study was in agreement with other studies' results [15,48,49,56]. Phosphatase activity was highest under weedy check compared to that under herbicide application, which might be due to the fact that under weedy check, bacterial biomass could be higher (data not presented); similar findings were reported by Majumdar et al. [82].

4.10. Soil Quality

From PC1, the permanganate oxidizable carbon was chosen as an indication. According to Culman et al. [83], $KMnO_4$-C represented a more refined soil C component. It might act as a precursor to long-term total SOC alterations under various management practices [44]. Organic stuff that is more labile and less resistant, such as polysaccharides and humic compounds, can be seen in $KMnO_4$-C [16]. The TOC, often known as the carbon bound in organic molecules in soil, was chosen as the second signal from PC2. These organic components could come from both endogenous and external sources [84]. Despite the minimal application of TOC in SQI that was discovered, the various types of carbon were used by many workers. The different levels of CA practices influenced the soil quality index at the end of the four crop cycles. As discussed above, the SQI in the present investigation was influenced by shortlisted parameters and the adoption of CA resulted in improvement in all parameters. Earlier studies by some researchers also reported similar results [48,85].

5. Conclusions

The adoption of conservation agriculture (CA) practices has demonstrated compelling advantages in enhancing soil quality and carbon dynamics. Notably, full CA treatment consistently yielded superior outcomes across various parameters compared to conventional agriculture and partial CA practices. These included increased soil organic carbon content, labile carbon fractions, active carbon pools with enhanced enzymatic activities, and soil quality indices. However, weed management practices influenced mainly very labile pools of carbon. The above findings underscore the potential of CA to mitigate soil degradation and enhance the sustainability of rice-based cropping systems. As agriculture faces the challenges of environmental preservation and food security, embracing CA emerges as a promising strategy to ensure productive and resilient agricultural practices while safeguarding soil health and ecological balance.

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