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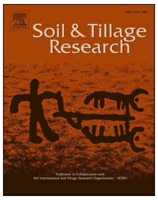

Soil quality indices in a conservation agriculture based rice-mustard cropping system in North-western Indo-Gangetic Plains

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ABSTRACT

The systematic research on the effect of medium-term conservation agriculture (CA) on soil quality, especially under the rice (*Oryza sativa* L.)-based cropping systems is limited. Hence, the specific objective of the study was to develop soil quality indices with key soil physical, chemical and biological indicators under the conservation and conventional tillage practices in a rice–mustard [*Brassica juncea* (L.) Czern.] cropping system. Eight treatment combinations including tillage and crop establishment, crop residue and cropping system intensification with inclusion of short duration summer mungbean [*Vigna radiata* (L.) Wilczek] were adopted in rice - mustard cropping system in hot semi-arid, sub-tropical north-western Indo-Gangetic Plains agro-ecoregion of India. Soil samples collected from topsoil (0–5 cm) and 5–15 cm soil layer were analyzed for 15 physical, chemical and biological properties to develop unified soil quality index (SQI) through principal component analysis (PCA). The highest SQI was obtained in the zero till direct seeded rice (ZTDSR) – zero till mustard (ZTM) –ZT summer mungbean (ZTSMB (+R) (mungbean residue in ZTDSR - rice residue in ZTM- mustard residue in ZTSMB) treatment followed by the ZTDSR + BM (brown manuring) – ZTM (+R) (mustard residue in ZTDSR with BM – rice residue in ZTM). The lowest SQI was obtained in transplanted puddled rice (TPR) - conventional till mustard (CTM) for both soil layers. The identified key indicators for SQI in this Inceptisol were saturated hydraulic conductivity (K_s), pH, total N, available P, and available K. Besides, the plots under ZTDSR – ZTM – ZTSMB (+R) resulted in 14 % higher total organic C in topsoil and 28 % higher aggregate stability than the TPR - CTM plots. This ZTDSR – ZTM -ZTSMB (+R) treatment had 65 % higher surface soil microbial biomass C than the TPR – CTM treatment. The ZTDSR – ZTM -ZTSMB (+R) treatment also led to higher K_s, which was in the order of triple ZT > double ZT > ZT > conventional tillage. Thus, the medium-term CA with triple or double zero tillage with crop residue retention could lead to maintain agricultural sustainability under rice-mustard system. Hence, it may be recommended to the farmers for adoption.

1. Introduction

Rice (*Oryza sativa* L.)-based cropping systems are dominant in the Indo-Gangetic Plains (IGP) of South Asia. Intensive tillage practices including puddling (repetitive wet tillage in ponding water) have tremendous adverse impacts on soil quality, especially with reference to rice growing belts under tropical and sub-tropical climates (Chauhan et al., 2012). In general, in rice–growing regions, water requirement is high due to the growing of puddled transplanted rice (Mohammad et al., 2018), which is responsible for poor soil physical structure. Also, it is a source of greenhouse gas emission (Gupta et al., 2016; Hazra and Chandra, 2016), coupled with negative effect on soil microbial ecology (Bhattacharyya. et al., 2007; Bhattacharyya et al., 2012). Thus, it subsequently leads to stagnation of yield and unsustainability (Gupta et al.,

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2015). Besides, improper nutrient management (Shahid et al., 2013) and limited crop diversification without retention of crop residues have aggravated deterioration in soil quality. Also, conventional cultivation of the post-rainy season mustard requires large number of tillage operations, which delays the sowing of mustard. Adoption of zero tillage can ensure sowing of mustard in time, which results in higher yield (Rathore et al., 1999; Das et al., 2020). Thus, there is a need to study long-term sustainable crop management practices through introducing conservation agriculture (CA) for yield benefit and soil quality improvement.

In South Asia, the benefits of CA in terms of resource conservation, enhanced soil quality along with sustainable crop productivity with profitability have been documented (Das et al., 2016, 2018, 2020). However, the productivity/ yield benefit coupled with profitability under CA over conventional practice is always a debatable issue in spite of its several merits. Many studies in the past reported the benefits of CA on soil properties and sustainability of rice-based systems. However, the systematic study on CA impacts on soil quality index (SQI) under rice-based system of sub-tropical India is limited. Soil quality is altogether the function of different physicochemical and biological characteristics of soils, and, therefore, cannot be measured directly. It is pertinent to understand and identify the specific soil characteristics related to soil functions for the sustainable crop production under agricultural ecosystem. A range of soil characterizing parameters from crop management-induced changes on soil properties (Sharma et al., 2008; Takoutsing et al., 2016) have been identified as soil quality indicators (Mukherjee and Lal, 2014). Therefore, selection of appropriate indicators related to soil functions sensitive to the management practices become the most crucial step for development of SQI. Hence, monitoring the changes of SQI as an effect of different management practices would serve the purpose of its (CA) feasibility and sustainability under Indian tropical and subtropical cropping systems. But, the impact of CA adopting double and triple zero till cropping systems with crop residue retention on soil quality indicators has not been adequately studied in the rice–mustard system. Hence, we examined a field experiment (2010–2018) of eight years old to evaluate the effect of CA and conventional tillage (CT) under a rice-mustard cropping system in hot semi-arid, subtropical north-western IGP agro-ecoregion of India. The specific objectives of the study were: (i) to develop SQI under CA and CT management practices; and (ii) to specify the key soil indicators of soil quality under different CA and CT practices in a rice–based cropping system in the 0−5 and 5−15 cm soil layers. We hypothesised that: (i) different soil quality indicators (physical, chemical and biological) would likely be affected by different CA and CT based crop establishment practices; (ii) double and triple zero till systems with residue retention would have better SQI than the conventional one; and (iii) there would be positive quantitative relationships between the system productivity [in terms of rice equivalent yield (REY), rice yield (RY), mustard yield (MY)] and SQI. In a novel approach, this work is related to the development of SQI, especially under different CA and CT management practices in a rice-mustard cropping system of sub-tropical India (Inceptisols). The obtained indices may also be useful in the assessment of soil quality for similar soils under similar agro-climatic conditions and may be extended further towards similar soils all over the world.

2. Materials and methods

2.1. Experimental site and treatment details

The field study was started in 2010−11 at the ICAR-Indian Agricultural Research Institute (IARI), New Delhi (28°35’N, 77°12’E, altitude 229 m above sea level) under sub-tropical semi-arid climate. The hottest months are May and June (40−44 °C), whereas the coldest month is January. Almost 80 % of the total rainfall (900 mm) is received during July to September (south-west monsoon) and the rest during December and February (western disturbance). After the uniformity trial, ten soil samples (0−15 cm depth) were randomly collected during June 2010 and analyzed for pH, organic C and different nutrients contents (Table 1). The pH of experimental soil was 7.9 (sandy clay loam in texture) with 5.4 g kg^{-1} organic C (Walkley and Black, 1934), 25.6 g kg^{-1} available P and 260.3 g kg^{-1} available K.

During the field experimentation (2010−11 to 2017−18), eight treatments (Table 2) were arranged in a randomized block design in triplicates. In the first three years (2010−11 to 2012−13), rice-maize cropping system was followed. The system was changed to rice-mustard system from 2013−14 onwards as winter maize (*Zea mays*) was very much susceptible to frost damage in this region, and then, continued for five years till 2017−18. Four double cropping ZT and two triple cropping ZT systems with or without crop residue retention were adopted as treatments along with two conventional till systems (control). The double/triple ZT systems with residue retention were considered as the CA practice with three principles (minimum soil disturbance, residue retention on the soil surface, and crop rotation). The double cropping ZT system with residue retention involved ZT direct-seeded rice (DSR) with 40 % anchored residue of mustard (during rainy season) - ZT mustard (ZTM) with 40 % anchored residue of rice (during winter). The triple cropping ZT system involved ZT DSR with 100 % anchored residue of mungbean (during rainy season) – ZTM with 40 % anchored residue of rice (during winter) – ZT summer mungbean with 40 % anchored residue of mustard (during summer). The plot size was 14.0 m × 9.0 m. The varieties of rice, mustard and mungbean were PRH 10, P 25, and SML 668, respectively. Rice, mustard and mungbean were sown using a turbo seeder with 20, 4 and 20 kg seed ha^{-1}, respectively. Rice and mungbean were sown at 20 cm row spacing, while mustard was sown in 40 cm rows. The recommended doses of fertilizers per hectare (ha) for rice were: 120 kg N, 26 kg P and 33 kg K; for mustard, these were 80 kg N, and 18 kg P. For the mungbean crop, diammonium phosphate at 100 kg ha^{-1} was applied at sowing. The full amount of P and K and 50 % of the total N were applied at the time of transplanting/ sowing (as applicable) of rice/mustard. In rice, the remaining 50 % N was applied at tillering and at panicle initiation stages. In mustard, the remaining N was applied after first irrigation at 30 days after sowing (DAS). For brown manuring practice (Susha et al., 2018), rice (in rows) and *Sesbania aculeata* (broadcasted) were sown on the same day, grown together as co-culture, and then *Sesbania* plants were killed at 25 DAS by applying 2,4-D at 0.5 kg a.i. ha^{-1} (Sen et al., 2018). The recommended practices using herbicides were followed for controlling weeds in rice (Baghel et al., 2018), mustard and mungbean (Das, 2008). Border strip method was followed for irrigating the crops. A 2.0–2.5 cm standing water was maintained in TPR through irrigation almost at every 3 days, while irrigation at 50 % soil moisture depletion was applied to DSR. For the mustard crop, 2–4 irrigations and for mungbean, 2–3 irrigations were given, depending on the frequency and intensity of rainfall received during the crop growing period (Das et al., 2020).

Table 1
Initial soil properties (0-15 cm soil layer) and climatic parameters of the experimental site.

Climatic parameters	
Maximum temperature (°C) in summer	40 to 44
Minimum temperature (°C) in winter	3 to 8
Mean annual rainfall (mm)	900
Wind velocity (kmh^{-1}) throughout the year	3.5 kmh^{-1} to 4.3 kmh^{-1}
Soil parameters	
Taxonomical classification	Typic Haplaquept
Texture	Sandy clay loam
pH	7.9
Walkley and Black carbon (g kg^{-1})	5.4
Bulk density (Mg m^{-3})	1.50

Table 2
Treatments/conservation agriculture practices adopted in the rice–mustard cropping system during 2013/14 - 2017/18.

Treatments*	Operations performed	Treatment short forms
Zero till direct seeded rice (ZTDSR) – zero till mustard (ZTM)	Zero till sowing of DSR was done using a turbo seeder with 20 kg seed ha^{-1} at a row-spacing of 20 cm. Rice seeds were placed at 5–6 cm distance by turbo seeder. ZTM was sown using turbo seeder with 5 kg seed ha^{-1} at a row-spacing of 40 cm. The turbo seeder was calibrated for rice and mustard seed rate before sowing.	ZTDSR-ZTM
ZTDSR with *Sesbania* brown manuring (BM) – ZTM	*Sesbania aculeata* (Dhaincha) seed as a mixed-sown brown manure crop was broad casted manually after sowing of DSR. It was allowed to grow with rice for about 25 days after sowing (DAS), which produced above-ground biomass weight of 1.5–2.0 t ha^{-1} and provided ~40 kg N ha^{-1}. After 25 DAS, *Sesbania* was sprayed with 2, 4-D at 0.5 kg ha^{-1}, which resulted in gradual drying up of *Sesbania* plants. *Sesbania* performs as live and dead mulch for around 40 DAS with rice. It showed smothering effect on weeds and also slightly suppressed the initial seedlings growth of rice, but resulted in relatively higher yields than in DSR without *Sesbania*.	ZTDSR + BM-ZTM
Mustard residue in ZTDSR – rice residue in ZTM	In addition to ZTDSR - ZTM (mentioned above), 40 % mustard residue in rice and 40 % rice residue in mustard were retained on the surface.	ZTDSR-ZTM (+R)
Mustard residue in ZTDSR with BM – rice residue in ZTM	In addition to the ZTDSR + BM – ZTM (mentioned above), mustard and rice residues were retained at 40 % each on the surface.	ZTDSR + BM-ZTM(+R)
ZTDSR –ZTM- ZT summer mungbean (ZTSMB)	Each crop was sown with turbo seeder in ZT condition. After mustard harvest, a short duration (60–65 days) mungbean (*Vigna radiata*) cv. SML 668 was grown under zero-till conditions. Mungbean sowing was performed during summer (middle of April). After picking its matured pods, whole plants were removed after 60–65 DAS, and DSR was sown.	ZTDSR-ZTM-ZTSMB
Mungbean residue in ZTDSR - rice residue in ZTM-Mustard residue in ZTSMB	Each crop was sown with turbo seeder in ZT condition. Three crops residue (i.e. 100 % mungbean residue to rice, 40 % rice residue to mustard, and 40 % mustard residue to mungbean crop) were retained. Mungbean shoots provided a dry weight of ~1.6–2.0 t ha^{-1} and ~55 kg N ha^{-1} to soil.	ZTDSR-ZTM-ZTSMB (+R)
Transplanted puddled rice (TPR)-ZTM	In TPR, two diskings and two harrowings were done under aerobic soil conditions, and then soil was puddled with water for easy transplanting of rice seedlings in soft mud. Mustard was grown under ZT condition with turbo seeder without crop residue.	TPR-ZTM
TPR-conventional till mustard (CTM)	Practices as mentioned above were followed in TPR. Mustard was grown without residue under CT condition, following two disking and two harrowing. Manual broadcasting for mustard was performed in CT plots.	TPR-CTM

* Similar treatments with maize crop/maize residue in place of mustard crop/mustard residue were adopted during the initial three years (2010/11–2012/13) under rice-maize system with the fixed lay-out in the field.

2.2. *Soil sampling and methods of analysis*

Soil samples were collected using a core sampler (7.5 cm diameter) at two depths i.e., 0–5 cm and 5–15 cm, in triplicates from each plot of 8 treatments (thus total number of samples were 48) at the end of eight experimental years (on 30 June 2018). One set (the first set) of the wet soil samples was kept in a refrigerator at 4 °C for the analysis of biological parameters. The second set was air dried, processed, ground and passed through a 2 mm sieve for the analysis of soil chemical parameters, and the third set for soil physical parameters following standard protocols. The physical properties studied were the bulk density (BD), mean weight diameter (MWD), and field-saturated hydraulic conductivity (K_s). Undisturbed soil cores were used for BD determination (Black and Hartge, 1971). The MWD was determined following aggregate stability measurement in the laboratory by wet sieving method (Yoder, 1936) and K_s was measured in-situ using a Guelph Permeameter (Reynolds and Elrick, 1991; Reynolds et al., 2002). The studied chemical parameters were total soil organic carbon (SOC) and total N (analysed by the dry combustion method using a CHN analyser; Euro Vector, Euro EA3000 model) (Nelson and Sommers, 1982). Additionally, we measured soil pH in 1:2 soil/water suspension using a glass electrode (Page et al., 1982), oxidizable organic C by wet oxidation with potassium dichromate and sulfuric acid procedure (Walkley and Black, 1934), available P by Olsen's method (Olsen et al., 1954), available K through 1 M NH_4OAc extraction (Jackson, 1967), available Fe & Zn by extracting with DTPA (0.005 M) + triethanolamine (TEA) (0.1 M) + calcium chloride ($CaCl_2 \cdot 2H_2O$) (0.01 M) reagent (pH7.3) as suggested by Lindsay and Norvell (1978) and then determined by using atomic absorption spectrophotometer, and available B (hot-$CaCl_2$ extractable; Parker and Gardner, 1981). The biological parameters measured were soil microbial biomass C (MBC) using the chloroform fumigation-extraction method (Vance et al., 1987), and dehydrogenase activity (DHA) estimated by the release of triphenyl formazan from the reduction of 2,3, 5-triphenyl tetrazolium chloride (Dick et al., 1996).

2.3. *Rice-mustard system productivity*

In 2017, rice crop at maturity was harvested and sun dried. The total produce was weighed and recorded as total biomass after attaining constant weight. Then, these were threshed. After separating the grains, they were dried and weighed (approx. 12 % moisture content) for grain yield. Similarly, the yields of mustard and mungbean (for 2017–18) were recorded. The yield of the rice-mustard system without/with mungbean (as applicable to treatments) was expressed in terms of rice equivalent yield (REY). Here, the REY, along with rice yield (RY) and mustard yield (MY) were considered as the management goal for this rice-mustard cropping system to assess the soil quality following Lal et al. (2017). For determining system yield, the mustard/mungbean yields were converted into REY using Eq.1 (Das et al., 2018). The minimum support prices of rice, mustard, and mungbean, declared by the

Government of India, were used for determining the REY.

$$\text{REY of mustard} = [(\text{Mustard yield x price of mustard}) / (\text{Price of rice})] \quad (1)$$

2.4. *Computation of minimum data set (MDS) and soil quality index (SQI)*

Here, MDS was computed based on conceptual framework approach and as a primary management goal of "productivity" under rice–maize/mustard cropping system. A set of potential soil quality indicators are listed in Table 3 with their related soil functions in association with management goals. The soil quality indicators were selected based on established literature and expert opinion. These indicators were also chosen from the rice-based cropping system under similar soil and agro-ecological environment (Bhaduri and Purakayastha, 2014). The data obtained for all 15 soil quality attributes as affected by the CA were statistically analyzed (Gomez and Gomez, 1984) for level of significance by using Tukey's HSD test.

After statistical analysis, the parameters, which were found significant were subjected to principal component analysis (PCA) to convert it into an MDS through multivariate statistical technique (Andrews et al., 2002). According to the Brejeda et al. (2000), the principal components (PCs) with high eigen values would represent the variation as its best in the system. Consequently, the PCs with ≥ 1 eigen values were only considered (Kaiser, 1960) for this study. Then, for MDS, highly weighted factors with absolute values within 10 % of the highest weight were selected within each PC. Thereafter, these indicators were subjected to multiple regression analysis as independent variables and rice equivalent yield, rice yield and mustard yield as the dependent variables. Then, MDS were transformed through linear scoring function following Sharma et al. (2008), where 'more is better' approach for all MDS indicators were accepted. However, for the bulk density (BD), 'less is better' function was considered. Following this method, the chemical, biological and physical parameters (except BD) were given the score 1.0 having the highest values and for others, the observed value was divided by the highest value. For BD, the score 1.0 was assumed to be associated with lowest value. After transformation, the SQI (Fig. 1) value (Eq. 2) was calculated by multiplying the weightage of the MDS variables (Wi) from the PCA with the score (Si) of that variables. The score was obtained dividing variation (%) of each principal component to that of cumulative variation (%) for all the principal components selected for the analysis following Biswas et al. (2017).

Table 3
A subset of potential indicators for the soil functions and associated management goal.

Management Goal : Productivity	
Soil functions	Indicators
Physical stability	Mean weight diameter Bulk density
Water relations	Hydraulic conductivity Oxidizable carbon
Nutrients cycling	Total nitrogen Total carbon Total organic carbon Oxidizable carbon Available phosphorus Available potassium Available micronutrients Microbial biomass carbon Dehydrogenase activity
Resistance and resilience	Oxidizable carbon Bulk density Hydraulic conductivity
Biodiversity and habitat	Microbial biomass carbon Dehydrogenase activity

$$\mathrm{SQI} = \sum\nolimits_{i=0}^{n} (\mathrm{Wi} * \mathrm{Si}) \quad (2)$$

One assumption was made here that higher value of SQI was considered a better performance of soil functions with improved soil quality. Thereafter, calculation on the contribution of each key indicator towards SQI was done.

3. Results and discussion

3.1. *Physical soil quality parameters at the 0–5 and 5–15 cm depths*

The CA practices had significant effect on all the physical parameters of soil quality, namely, BD, MWD and K_s in both 0–5 and 5–15 cm soil layers (Table 4). Soil BD varied from 1.50 to 1.55 Mg m^{-3} in the 0–5 cm and was highest in the ZTDSR-ZTM treatment. In the lower soil layer (5–15 cm), its values were comparatively higher than those in the topsoil (0–5 cm) and varied from 1.52 to 1.57 Mg m^{-3}. Among the CA-based management practices, the treatments under ZTDSR-ZTM-ZTSMB (+R) had the lowest soil BD in both soil layers. This might be due to better aggregation and more pore space along with crop residue retention, resulting in lower bulk density than conventional tillage (Bhattacharyya et al., 2015; Choudhary et al., 2018). Again, the ZTDSR-ZTM-ZTSMB (+R) treatment (Table 4) resulted in highest MWD, i.e., 1.19 mm and 0.86 mm, respectively, in the 0–5 and 5–15 cm soil layers.

In the topsoil, MWD was ~28 % higher in the ZTDSR-ZTM-ZTSMB (+R) treatment than that of the TPR-CTM treatment (i.e., conventional till (CT) treatment), which had lowest MWD (Table 4). Higher MWD in the ZTDSR-ZTM-ZTSMB (+R) treatment might be due to higher activities of microorganisms under the ZT with residue from the three crops, including a legume residue, leading to more microbial biomass. The use of organic residues helped in increasing stability of aggregates as evident from the higher MWD values. Besides, reduction in tillage operation in the ZT also form stable soil aggregates along with reduction in disruption of soil macroaggregates by delaying macroaggregate turnover rate (Six et al., 2002), resulting in higher MWD in the top soil layer (Parihar et al., 2020). The K_s of the topsoil (0–5 cm) was in the order: triple ZT > double ZT > ZT > CT, irrespective of the presence or absence of the residues (Table 4). The differences in K_s values among triple and double ZT and CT were significant ($P < 0.05$). The K_s in the 5–15 cm soil layer also followed similar trend as observed in the upper layer (0–5 cm). It varied from 33 to 89 cm day^{-1}. The ZTDSR – ZTM-ZTSMB (+R) treatment resulted in significantly higher K_s than TPR-CTM and the remaining treatments in the 5–15 cm soil layer. Furthermore, all the residue retention plots had higher K_s than no residue plots. There was a significant reduction in K_s in the TPR-ZTM and TPR-CTM treatments in both soil layers. Parihar et al. (2020) also found similar results.

It is already established that the size and arrangement of soil pores and its continuity affect K_s. Therefore, the greater K_s of the topsoil under reduced tillage with residue retention might be owing to occurrence of bio-channels as evident from higher microbial activity in association with greater SOC accumulation on the surface soil leading to improved porosity as well as better pore continuity. Higher K_s in ZT soil might result from better pore continuity, because ZT soil had lesser number of larger pores (Bhattacharyya et al., 2006) in association with greater proportion of water stable aggregates (Singh et al., 1994). Parihar et al. (2020) also found that improved aggregation leads to continuity of soil pores and pore size distribution that resulted in greater Ks. An array of international literature supports the fact that there is an improvement in soil physical properties under ZT with residue retention under different soil and climatic conditions (Six et al., 2002; Li et al., 2011; Bhattacharyya et al., 2015; Jat et al., 2019; Parihar et al., 2020). In contrast, Castellini et al. (2019) reported that infiltration and hydraulic conductivity were lower under no-tillage than CT.

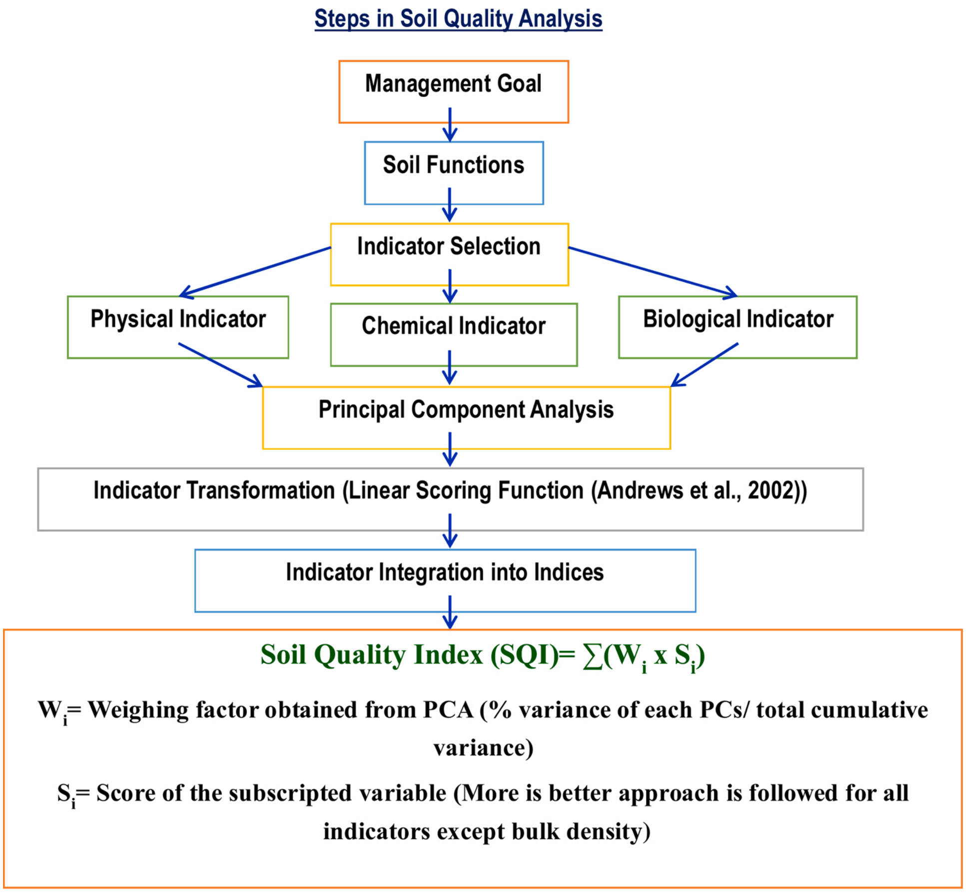

Fig. 1. Steps in soil quality analysis.

Table 4

Impact of conservation agriculture on the physical soil quality parameters in the 0-5 and 5-15 cm soil layer under the rice-mustard system.

Treatments	Soil physical parameters (0−5 cm)			Soil physical parameters (5−15 cm)		
	Bulk density (Mg m^{-3})	Mean weight diameter (mm)	Saturated hydraulic conductivity (cm day^{-1})	Bulk density (Mg m^{-3})	Mean weight diameter (mm)	Saturated hydraulic conductivity (cm day^{-1})
ZTDSR-ZTM	1.55a	1.01c	79bc	1.57a	0.68c	59.3bc
ZTDSR + BM-ZTM	1.53ab	1.08b	83bc	1.55ab	0.75b	63.3bc
ZTDSR-ZTM(+R)	1.53ab	1.07b	86ab	1.54bc	0.74d	66.3ab
ZTDSR + BM-ZTM (+R)	1.51ab	1.11b	87ab	1.53bc	0.78bc	67.3ab
ZTDSR-ZTM-ZTSMB	1.52ab	1.13ab	87ab	1.54bc	0.80ab	66.7ab
ZTDSR-ZTM-ZTSMB(+R)	1.50b	1.19a	109a	1.52c	0.86a	89.3a
TPR-ZTM	1.54ab	0.99c	62cd	1.56ab	0.66c	41.7cd
TPR-CTM	1.53ab	0.92d	54d	1.55ab	0.59d	33.7d

Means followed by a similar lower-case letter within a column for a management practice are not significantly different at $P < 0.05$ according toTukey's HSD. ZTDSR-ZTM = zerotill direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR –ZTM–ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM- mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

3.2. Biological soil quality parameters at the 0−5 and 5−15 cm depths

The CA-based treatments significantly influenced the biological soil quality parameters such as MBC and DHA at the 0−5 and 5−15 cm soil depths (Table 5). Monitoring of enzyme activity in a soil is essential to know the potential of the soil to carry out different complex biochemical processes to maintain soil fertility *vis-a-vis* soil quality. The plots under ZTDSR-ZTM-ZTSMB (+R) treatment resulted in 65 % higher MBC in topsoil than the plots under TPR-CTM. The MBC was comparatively lower in the 5−15 cm than in the 0−5 cm soil layer. It varied from 536 to 762 mg kg^{-1} in the 5−15 cm depth of soil. In this soil layer, the plots under ZTDSR-ZTM-ZTSMB with and without residue, ZTDSR-ZTM (+R) and ZTDSR + BM-ZTM (+R) led to significantly higher MBC than other plots. Therefore, plots without residue resulted in significantly lower MBC than the crop residue and brown manuring treated plots. Soil microbial activity and biochemical processes largely depend on SOC and various soil management practices and lead to minor changes in SOC, which is often not measurable. That is why the crop residue and/or

Table 5
Impact of conservation agriculture on the biological soil quality parameters in the 0-5 and 5-15 cm soil layers under the rice-mustard system.

Treatments	Soil biological parameters (0–5 cm)		Soil biological parameters (5–15 cm)	
	Microbial biomass carbon (mg kg^{-1})	Dehydrogenase activity (μg TPF/g/24 h)	Microbial biomass carbon (mg kg^{-1})	Dehydrogenase activity (μg TPF/g/24 h)
ZTDSR-ZTM	604b	381d	550bc	303d
ZTDSR + BM-ZTM	643b	405c	588abc	328c
ZTDSR-ZTM (+R)	788a	422b	722ab	394b
ZTDSR + BM-ZTM (+R)	807a	409c	739a	401b
ZTDSR-ZTM-ZTSMB	827a	433ab	762a	418a
ZTDSR-ZTM-ZTSMB (+R)	851a	434a	702ac	422a
TPR-ZTM	564b	343e	553bc	321c
TPR-CTM	516b	315f	536c	301d

Means followed by a similar lower-case letter within a column for a management practice are not significantly different at $P < 0.05$ according toTukey's HSD. ZTDSR-ZTM = zerotill direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR –ZTM–ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM-mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

Sesbania residue retained plots had higher MBC and DHA. Apart from this, decomposition of crop residues under ZT is slow and thus, there is gradual accumulation of organic matter on soil surface resulting in higher MBC in upper soil surface (Choudhary et al., 2018). Data also indicated that the addition of residue helped to increase MBC, which is also considered as one of the labile pools of SOC. MBC can reflect the ability of soil how well it can accumulate and cycle the essential nutrients and soil organic matter (SOM) (Carter, 1992). Our findings are in conformity with that of Govaerts et al. (2007a,b), who observed that residue retention significantly increased MBC in the surface soil layer than the no residue treated plots in a sub-tropical soil under a long-term experiment. The continuous supply of C inputs through crop residues could serve as the energy source for the micro-organisms. This might be a reason why the residue-amended plots had greater enzyme activity compared with no residue plots.

The same was true for DHA in the CA-based management practices (Table 5), showing greater improvement in DHA in the topsoil (0–5 cm). The triple ZT cropping system (rice-mustard-mungbean) without or with residue of three crops [i.e., ZTDSR-ZTM-ZTSMB (+R)] resulted in significantly higher DHA than the TPR-ZTM and TPR-CTM plots at both depths. The ZTDSR-ZTM-ZTSMB (+R) treatment resulted in ~26 % and 37 % higher DHA than TPR-ZTM and TPR-CTM, respectively, in the 0–5 cm soil layer. Crop residue retention, inclusion of mungbean, and brown manuring plots had similar impact and improved soil enzymatic activity considerably. This might be due to the treatments having mungbean and *Sesbania* residue having more nutrients retention that led to higher DHA. The positive effect of CA practices on DHA might be due to greater cycling of nutrients coupled with better bio-chemical metabolism (Manjaiah and Singh, 2001). Spedding et al. (2004) also reported that a myriad of soil microorganisms flourished under well aggregated soil structures, improved K_s, MWD and improved hydro-thermal conditions of surface soils under ZT. On the other hand, Dey et al. (2016) reported that there is reduction in soil biological activities under CT due to intensive tillage operations coupled with lesser availability of fresh crop residues.

3.3. *Chemical soil quality parameters at 0–5 and 5–15 cm depths*

Soil pH of the experimental field was alkaline with slightly higher values in the topsoil (0–5 cm) than in the 5–15 cm soil layer (Tables 6 and 7). It varied from 8.24 to 8.51 and from 8.10 to 8.41 in the 0–5 and 5–15 cm soil layers, respectively, across the CA-based DSR treatments. Different crop residues (i.e., rice, mungbean, *Sesbania*, mustard) retained in these treatments might have led to variation in soil pH. The ZTDSR-ZTM-ZTSMB (+R) treatment resulted in highest total N, which was 8.8 % higher than that in the TPR-CTM treatment in the 0–5 cm soil layer (Table 6). This treatment also had highest total N in the 5–15 cm soil layer (Table 7). This result is in conformity with Dey et al. (2016), who reported that there was 9% increase of total N under CA-based rice-wheat system compared to CT. However, the ZTDSR-ZTM (+R) and ZTDSR-ZTM (both double cropping ZT systems with or without residues) plots had similar total N. This might be due to ZT could protect soil N in intra-aggregate spaces (Bhattacharyya et al., 2019). However, Bradford and Peterson (2000) reported that CA practices resulted in lower level of soil N because of greater immobilization by the residues left on the soil surface. This might be due to lower rates of N mineralization followed by higher rates of N immobilization in the soil as higher amounts of crop residues of varying C:N were added under CA (Page et al., 2020). The concentrations of total organic C (TOC) and oxidizable C (i.e., Walkley and Black carbon; WBC) in the surface soil layer followed almost similar trend to that of total N, and the ZTDSR-ZTM-ZTSMB (+R) treatment was superior, except in case of total soil carbon. This treatment resulted in significantly (by ~14 %) higher SOC than the TPR-CTM treatment (Table 6). It had also highest total carbon in the 5–15 cm soil layer, which was ~22 % higher than that in the TPR-CTM plots (Table 7). The total SOC in the 5–15 cm layer (Table 7) followed similar trend as total carbon and varied from 7.4–8.4 g kg^{1}. Again, the ZTDSR – ZTM–ZTSMB (+R) treatment led to ~14 % higher total SOC than the TPR-CTM treatment and had highest WBC (3.66 g kg^{-1}) in the 5–15 cm soil layer. The residues of rice, mustard and mungbean retained on the soil surface were subjected to decomposition and building up of total SOC in the topsoil in this CA practice. Also, this CA practice with highest WBC (6.39 g kg^{-1}) had significant impact on MBC in the 0–5 cm layer. Besides, all the residue retained plots had significantly higher WBC than the control plots (TPR-CTM). This might explain that residue-amended plots having higher microbial population could easily mineralize C and N, resulting in higher active C pools without affecting recalcitrant pool. Bhattacharyya et al. (2019) reported that in rice-based system, CA could protect the SOM from erosion by lowering the decomposition rate, in turn enhancing stability of SOC by virtue of its improved aggregation and better soil physico-chemical environment. In addition to this, fresh crop residues act as a continuous source of labile SOM, which get encapsulated in the process of macroaggregate formation (Jat et al., 2019; Dey et al., 2020; Parihar et al., 2020). Therefore, improved SOM under reduced tillage also acts as a buffer for N, P and K. Moreover, addition of residues having varying C:N under ZT also governs the mineralization/immobilisation cycle of nutrients, especially N (Meean et al., 2018; Pheap et al., 2019).

In all the CA-based treatments, soil available P was higher, varying from 44.2–84.7 kg P ha^{-1} in the 0–5 cm soil (Table 6) and from 31.5–47.0 kg P ha^{-1} in the 5–15 cm soil layer (Table 7) than in CT. The ZTDSR-ZTM-ZTSMB (+R) plots resulted in significantly higher available P in the 0–5 cm soil layer, but the ZTDSR + BM-ZTM (+R) plots had similar values. This treatment had 49 % higher available P than the TPR-CTM in the 5–15 cm soil layer. Higher available P might be due to release of organic acids during decomposition and solubilisation of

Table 6
Impact of conservation agriculture on chemical soil quality parameters in the 0-5 cm soil layer under the rice-mustard system.

Treatments	Soil chemical parameters (0–5 cm)									
	Total N (g kg^{-1})	Total C (g kg^{-1})	Total SOC (g kg^{-1})	WBC (g kg^{-1})	Av. P (kg ha^{-1})	Av. K (kg ha^{-1})	pH	Av. Zn (ppm)	Av. B (ppm)	Av. Fe (ppm)
ZTDSR-ZTM	0.718bc	9.21bc	8.07d	5.27f	75.0ab	352.8ab	8.24b	0.99ab	0.63bc	5.44d
ZTDSR + BM-ZTM	0.703d	10.98a	7.92e	5.62c	53.2bc	350.1ab	8.3ab	0.94b	0.51c	5.10e
ZTDSR-ZTM(+R)	0.715c	9.17c	8.25c	5.70b	55.5bc	371.0ab	8.43ab	1.05ab	0.71ab	6.96a
ZTDSR + BM-ZTM (+R)	0.728b	9.65abc	8.36b	5.50d	79.0ab	397.2a	8.36ab	0.95ab	0.52c	5.90c
ZTDSR-ZTM-ZTSMB	0.695de	9.95abc	7.63g	4.81g	51.7bc	347.5ab	8.32ab	1.01ab	0.65bc	6.50b
ZTDSR-ZTM-ZTSMB (+R)	0.740a	10.59ab	8.78a	6.39a	84.7a	388.0a	8.51a	1.15a	0.87a	7.07a
TPR-ZTM	0.688e	9.86abc	7.68f	5.39e	50.8bc	290.1ab	8.46a	0.93b	0.50c	4.70f
TPR-CTM	0.685e	10.74a	7.53h	5.26f	44.2c	271.4b	8.38ab	0.93b	0.53c	4.62f

Means followed by a similar lower-case letter within a column for a management practice are not significantly different at $P < 0.05$ according toTukey's HSD. ZTDSR-ZTM = zerotill direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR –ZTM–ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM- mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

Table 7
Impact of conservation agriculture on chemical soil quality parameters in the 5-15 cm soil layer under the rice-mustard system.

Treatments	Soil chemical parameters (5–15 cm)									
	Total N (g kg^{-1})	Total C (g kg^{-1})	Total SOC (g kg^{-1})	WBC (g kg^{-1})	Av. P (kg ha^{-1})	Av. K (kg ha^{-1})	pH	Av. Zn (ppm)	Av. B (ppm)	Av. Fe (ppm)
ZTDSR-ZTM	0.64abc	9.74ab	7.9ab	3.02e	42.0ab	269.6abc	8.10b	0.94abc	0.51b	5.24d
ZTDSR + BM-ZTM	0.62abc	9.09ab	7.7ab	3.05e	40.0ab	247.6abc	8.12b	0.88bc	0.50b	4.92e
ZTDSR-ZTM (+R)	0.66abc	9.37ab	8.1ab	3.49b	44.2ab	285.8ab	8.24ab	0.96ab	0.65a	6.50b
ZTDSR + BM-ZTM (+R)	0.69ab	10.36a	8.3ab	3.38c	44.8ab	287.2ab	8.21ab	0.89bc	0.51b	5.36d
ZTDSR-ZTM-ZTSMB	0.61bc	9.67ab	7.6ab	3.18d	38.2ab	229.6bc	8.15b	0.95abc	0.55ab	6.12c
ZTDSR-ZTM-ZTSMB (+R)	0.70a	10.43a	8.4a	3.66a	47.0a	299.7a	8.41a	0.99a	0.68a	6.80a
TPR-ZTM	0.61bc	8.53b	7.5ab	3.20d	39.7ab	224.6bc	8.18b	0.88bc	0.50b	4.56f
TPR-CTM	0.60c	8.52b	7.4b	3.02e	31.5b	201.9c	8.23ab	0.87c	0.50b	4.54f

Means followed by a similar lower-case letter within a column for a management practice are not significantly different at $P < 0.05$ according toTukey's HSD. ZTDSR-ZTM = zerotill direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR –ZTM–ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM- mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

native P in residue-amended plots. Furthermore, enhanced SOM with fresh residue retention under CA system with reduced tillage ensures minimal soil mixing of the applied fertiliser soluble P leading to less chances of fixation, adsorption and followed by precipitation, by formation of soluble phosphate-humate complexes, which enhance the lability and availability of soil P (Piegholdt et al., 2013; Dorneles et al., 2015). However, under CT, the availability of labile P is reduced due to maximum soil mixing (Kumawat et al., 2018). Available K varied from 271 to 397 kg ha^{-1} in the 0–5 cm layer and from 201 to 299 kg ha^{-1} in the 5–15 cm layer across the treatments (Tables 6 and 7). All rice residue-amended plots had higher available K as rice residues added 175 kg K ha^{-1} annually. According to Meean et al. (2018), under the CA practices, cereal residues supply higher amount of K to soil through decomposition as they have higher K concentration in their biomass. The highest available K was observed in the ZTDSR-ZTM-ZTSMB (+R) treatment in both the soil layers. Parihar et al. (2020) also reported that there was improved availability of soil N, P and K under CA system by virtue of its better soil aggregation, thereby protection of aggregate associated SOM along with N, P, and K in the aggregate associated fractions, further decreasing their losses from the soil.

Soil micronutrients (Zn, B, & Fe) were also significantly affected by the CA practices. Available Zn varied from 0.93 to 1.15 ppm and from 0.87 to 0.99 ppm, respectively, in the 0–5 and 5–15 cm soil layers across the treatments (Tables 6 and 7). The ZTDSR – ZTM-ZTSMB (+R) resulted in significantly higher available Zn than TPR-ZTM and TPR-CTM. Again, available B was highest in this treatment, and its values (~0.87 and 0.68 ppm in the 0–5 and 5–15 cm, respectively) were significantly higher than those in other treatments, except the ZTDSR-ZTM (+R) treatment (Tables 6 and 7). Available Fe also followed similar trend as the available Zn. It varied from 4.62 to 7.07 ppm and from 4.54 to 6.8 ppm, respectively, in the topsoil and 5–15 cm soil layer (Tables 6 and 7). Franzluebbers and Hons (1996) also found higher concentrations of micronutrients (Zn, Fe, Cu and Mn) under ZT with residue retention compared with CT in the surface soil. On the contrary, Govaerts et al. (2007a,b) reported that tillage practices had no significant impact on the concentration of extractable Fe, Mn and Cu, except Zn in the 0–5 cm layer of permanent bed planting compared to CT with full residue retention. The results similar to our study were reported by Du Preez et al. (2001). Thus, this study was conclusive that the CA practices with ZT and crop residues on a long-term basis could help in building up of soil fertility and restoration of soil health in rice-mustard system. We observed that, among the CA-based practices, the ZTDSR-ZTM-ZTSMB (+R) treatment was superior to other treatments. It not only improved soil physical, chemical, and biological parameters, and overall soil fertility in topsoil, but also significantly influenced these soil properties in the 5–15 cm soil layer.

3.4. Key indicators and SQI for 0–5 cm soil layer

Under this study, 15 important soil quality parameters were subjected to principal component analysis (PCA) to measure the soil quality indices among the treatments. In the PCA, only four principal components (PCs) having eigen values > 1 contributing to ~93 % variation in the MDS, and qualified to be the major components in this study (Table 8). Based on these, the K_s qualified to be highly weighted variable in PC1, whereas pH and available P qualified as the highly weighted variable in the PC2 and PC3, respectively. In PC4, total N was highly weighted. One variable each from PC1 to PC4 having higher factor loadings was considered as sensitive key indicators for the MDS, normalized and transformed through linear scoring functions (Sharma et al., 2008). The weighted factors for PC1, PC2, PC3 and PC4 were 0.686, 0.137, 0.098 and 0.079, respectively (Table 8). The SQI was computed by summing up the observations of the scores of each weighted MDS indicators using Eq.3.

SQI = $\sum$ [(Saturated hydraulic conductivity score*0.686) + (pH score*0.137) + (Available P score*0.098) + (Total N score* 0.079)] (3)

The SQI varied from 0.596 to 1.00 across the management practices in the rice-mustard system (Fig. 2). The relative order of performance of CA management practices towards influencing soil quality in terms of SQI was: ZTDSR – ZTM – ZTSMB(+R)>ZTDSR + BM – ZTM(+R)> ZTDSR – ZTM(+R)>ZTDSR – ZTM – ZTSMB > ZTDSR - ZTM = ZTDSR + BM – ZTM > TPR – ZTM > TPR-CTM. The contribution of K_s (56–69 %) towards SQI value was highest (Fig. 3), followed by pH (14–23 %), total N (8–12 %) and available P (7–11 %).

3.5. *Key indicators and SQI for 5−15 cm soil layer*

In the 5−15 cm soil layer too, 15 important soil parameters were considered for PCA, but only three PCs with eigen values > 1 explaining 88.8 % variation in the data set were considered as major components (Table 9). Again K_s in PC1, and available K in PC2 and pH in PC3 were qualified as the maximum weighted variables. As all these three parameters had higher factor loadings, they were also considered as sensitive key indicators for MDS for enumerating SQI. Then they were undergone transformation using linear scoring function. The weighted factors emerged were 0.811 for PC1, 0.103 for PC2, and 0.086 for PC3 (Table 9). To obtain SQI, the weighted MDS indicator scores for each observation were summed up using Eq. 4.

SQI=$\sum$(Saturated hydraulic conductivity score*0.811)+(Available K score*0.103)+(pH score*0.086) (4)

Table 8
Principal component analysis of soil quality parameters as influenced by conservation agriculture in the 0-5 cm soil layer under the rice-mustard system.

Parameter	PC1	PC2	PC3	PC4
Total Eigen values	9.563	1.911	1.37	1.101
Variance (%)	63.753	12.737	9.134	7.337
Cumulative (%)	63.753	76.49	85.624	92.962
Eigen vector				
Total N (g kg^{-1})	0.041	0.484	0.289	0.515
Total carbon (g kg^{-1})	−0.289	−0.056	−0.347	0.148
Total soil organic carbon ((g kg^{-1})	−0.245	−0.085	−0.433	0.232
Walkley Black carbon (g kg^{-1})	−0.286	−0.264	−0.075	0.202
Available P (kg ha^{-1})	−0.116	0.557	0.025	−0.315
Available K (kg ha^{-1})	−0.292	0.075	−0.337	0.085
pH	−0.214	0.419	−0.323	0.074
Zn (ppm)	−0.280	0.143	0.018	−0.348
B (ppm)	−0.263	0.130	0.009	−0.407
Fe (ppm)	−0.290	−0.097	0.193	−0.313
Bulk density (Mg m^{-3})	−0.289	−0.137	0.303	−0.018
Mean weight diameter (mm)	−0.277	−0.241	0.273	0.040
Hydraulic conductivity (cm day^{-1})	0.230	−0.247	−0.308	−0.277
Microbial biomass carbon (mg kg^{-1})	−0.292	−0.062	0.282	0.176
Dehydrogenase activity (μg TPF/g/24 h)	−0.313	−0.070	0.077	0.107

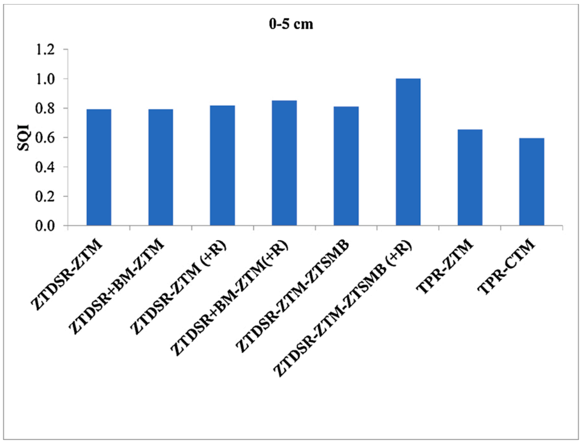

Fig. 2. Impact of conservation agriculture on soil quality indices (SQI) in the 0-5 cm soil layer under the rice-mustard system.
ZTDSR-ZTM = zero till direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR – ZTM – ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM-mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

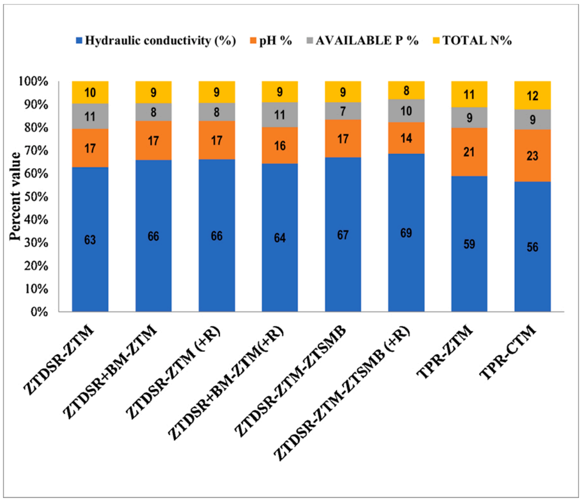

Fig. 3. Per cent contributions of key indicators to soil quality indices in the 0-5 cm soil layer under the rice-mustard system.
ZTDSR-ZTM = zero till direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR – ZTM – ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM-mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

The estimated SQI varied from 0.46 to 1.00 under different CA management practices in rice –mustard system (Fig. 4). The relative order of performance of CA management practices, influencing soil quality in terms of SQI was: ZTDSR – ZTM-ZTSMB(+R)>ZTDSR + BM – ZTM(+R)>ZTDSR – ZTM(+R)>ZTDSR – ZTM –ZTSMB > ZTDSR + BM – ZTM > ZTDSR – ZTM > TPR – ZTM > TPR-CTM. The contribution of K_s (67–81 %) towards SQI value was highest (Fig. 5), followed by pH (9–18 %), and available K (10−15%). Thus, the sensitive key indicators for soil quality indices were K_s, pH, total N, available P and available K for both the soil layers (i.e., 0−5 and 5−15 cm). Among these limited indicators, K_s was the key indicator among the physical soil quality attributes. Being a dynamic property owing to its influential effect on soil water, porosity,

Table 9
Principal component analysis of soil quality parameters as influenced by conservation agriculture in the 5-15 cm soil layer under the rice-mustard system.

Parameter	PC1	PC2	PC3
Total Eigen values	10.807	1.378	1.143
Variance (%)	72.045	9.185	7.622
Cumulative (%)	72.045	81.23	88.851
Eigen vector			
Total N (g kg^{-1})	−0.262	−0.231	0.257
Total carbon (g kg^{-1})	−0.269	−0.298	−0.151
Total soil organic carbon (g kg^{-1})	−0.258	−0.385	−0.011
WalkleyBlack carbon (g kg^{-1})	−0.263	−0.410	−0.062
Available P (kg ha^{-1})	−0.204	0.284	−0.562
Available K (kg ha^{-1})	−0.275	−0.294	−0.143
pH	−0.276	0.109	−0.278
Zn (ppm)	−0.239	0.089	−0.054
B (ppm)	−0.252	0.220	−0.340
Fe (ppm)	−0.275	0.191	0.019
Bulk density (Mg m^{-3})	−0.241	0.258	0.402
Mean weight diameter (mm)	−0.266	0.301	0.261
Hydraulic conductivity (cm day^{-1})	0.229	−0.316	−0.044
Microbial biomass carbon (mg kg^{-1})	−0.269	0.079	0.335
Dehydrogenase activity (μg TPF/g/24 h)	−0.283	−0.085	0.177

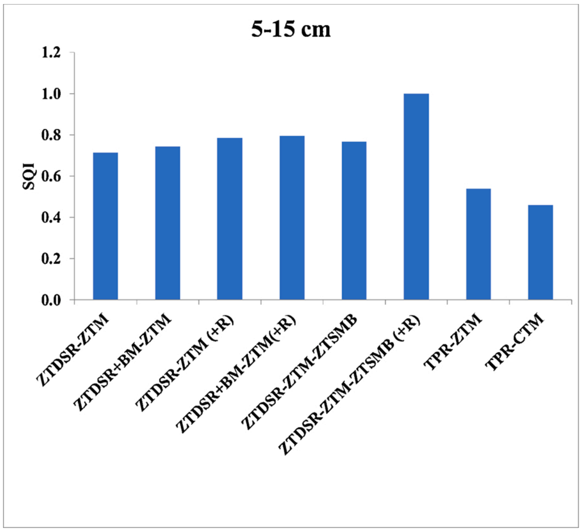

Fig. 4. Impact of conservation agriculture on soil quality Indices (SQI) in the 5-15 cm soil layer under the rice-mustard system.
ZTDSR-ZTM = zero till direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR – ZTM – ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM-mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

BD etc, K_s plays an important role, regulating soil water-air relationship, especially the arrangement of soil pores and macropores continuity (Bhattacharya et al., 2006). Therefore, it needs to be monitored periodically (Lou, 2002; Dam et al., 2005; Paz-Kagan et al., 2014). Soil pH is also estimated as another sensitive key indicator (Salomé et al., 2016; Biswas et al., 2017) next to K_s, which might be due to its role in influencing many soil properties/ processes. In addition to regulating soil nutrients availability (Schoenholtz et al., 2000), pH governs the microbial activity and turnover of organic matter (Arias et al., 2005). There is meagre information regarding the particular processes, which are primarily affected by the variation in pH. In this study, soil pH was slightly alkaline. If this soil becomes either too acidic or highly alkaline, it will affect the soil quality. Therefore, regular or periodical monitoring of soil pH should be emphasized.

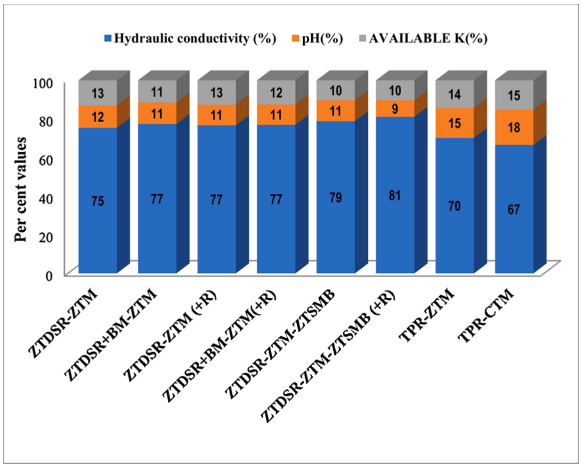

Fig. 5. Per cent contributions of key indicators to soil quality indices in the 5-15 cm soil layer under the rice-mustard system.
ZTDSR-ZTM = zero till direct seeded rice (ZTDSR) – zero till mustard (ZTM); ZTDSR + BM-ZTM = ZTDSR with Sesbania brown manuring (BM) – ZTM; ZTDSR-ZTM (+R) = mustard residue in ZTDSR – rice residue in ZTM; ZTDSR + BM-ZTM (+R) = mustard residue in ZTDSR with BM – rice residue in ZTM; ZTDSR-ZTM-ZTSMB = ZTDSR – ZTM – ZT summer mungbean (ZTSMB); ZTDSR-ZTM-ZTSMB (+R) = mungbean residue in ZTDSR - rice residue in ZTM-mustard residue in ZTSMB; TPR–ZTM = transplanted puddled rice (TPR)-ZTM; TPR-CTM = TPR-conventional till mustard (CTM).

Total N, available P and available K found to be the key indicators among soil chemical attributes (Askari and Holden, 2015; Salomé et al., 2016). In the past, Andrews et al. (2002) reported total N as one of the key indicators of soil quality and established its direct relationship with plant growth. The SOM directly affects N availability, but under Inceptisols, SOM is subjected to loss because of oxidation under high temperature and intensive cropping (Bhattacharyya et al., 2004; Mandal et al., 2008). Therefore, these soils should be properly managed by improving its organic matter and N along with other essential nutrients to sustain soil quality (Haynes, 1999). One of the selected chemical indicators was available P, which is essential for crop growth since it is involved in energy transfer reactions. Phosphorous is directly involved in photosynthesis, respiration, other metabolic pathways, division of cells, root development, and quality of grains, etc (Tisdale et al., 1993). Merrington et al. (2004) opined that P was one of the major yield limiting factors for agricultural crops. Available K plays important role in osmo-regulation of plants by making the plants tolerant to drought. Its deficiency may lead to susceptibility of plants towards drought. Furthermore, tillage practices can affect the K availability by modifying soil aeration and temperature (Sharma et al., 2005; Meean et al., 2018). Bünemann et al. (2018) also reported that soil pH, total organic carbon, available P, parameters related to soil water, available K, total N were the most frequently proposed soil quality indicators. They also conveyed that key biological soil quality indicators were absent from 40 % of the reviewed MDS.

3.6. Quantitative relationships between REY, RY, MY and SQI

Quantitative and predictive relationship between REY (rice equivalent yield) and SQI (Fig. 6a and b), MY (mustard yield) and SQI (Fig. 7a and b), and RY (rice yield) and SQI (Fig. 8a and b) under the long-term CA practices were developed separately for each soil layers for validation purpose. Here crop productivities of 2017−18 were considered. For this, REY, RY and MY were considered as dependent variables (y) and SQI (x) as independent variable under different CA management practices to fit the regression equations separately for each layer. The estimated regression coefficients were significant, with $R^2 = 0.63$ for the

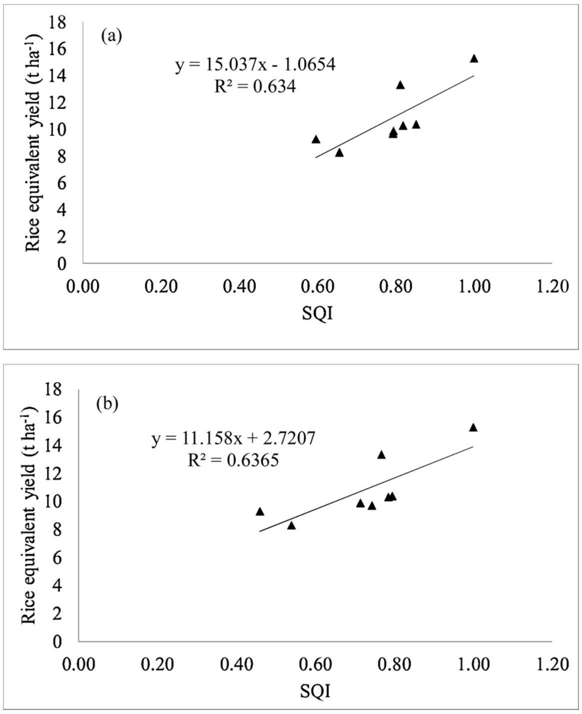

Fig. 6. Validation of soil quality indices (SQI) with rice equivalent yield (t ha^{-1}) under the rice-mustard system in the (a) 0-5 cm and (b) 5-15 cm soil layer (n = 8, P = 1).

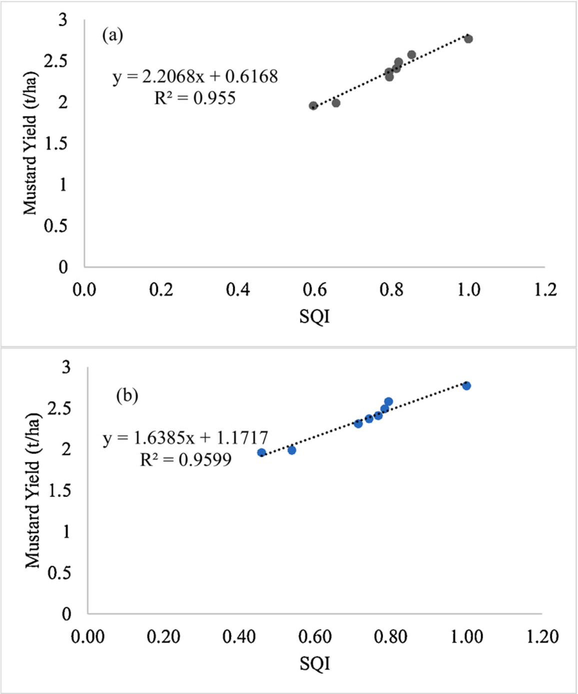

Fig. 7. Validation of soil quality indices (SQI) with mustard yield (t ha^{-1}) under the rice-mustard system in the (a) 0-5 cm and (b) 5-15 cm soil layer (n = 8, P = 1).

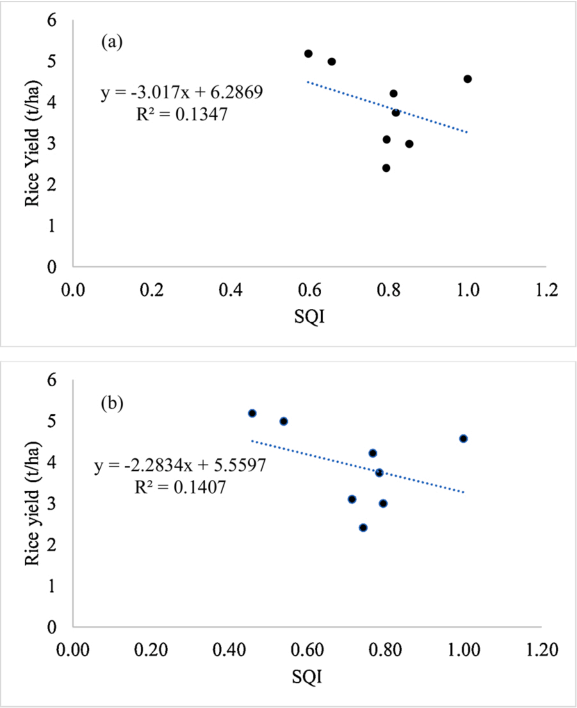

Fig. 8. Validation of soil quality indices (SQI) with rice yield (t ha^{-1}) under the rice-mustard system in the (a) 0-5 cm and (b) 5-15 cm soil layer (n = 8, P = 1).

0–5 cm, and $R^2 = 0.63$ for 5–15 cm soil layer for REY (Fig. 6a and b) and $R^2 = 0.95$ for the 0–5 cm, and $R^2 = 0.95$ for 5–15 cm soil layer for MY (Fig. 7a and b). However, for RY, the regression coefficients were not significant with $R^2 = 0.13$ for the 0–5 cm, and $R^2 = 0.14$ for 5–15 cm soil layer (Fig. 8a and b). In the north-western IGP, the tendency of yield penalty with DSR has been reported (Gathala et al., 2011; Baghel et al., 2018; Das et al., 2020). A negative trend in rice yield with DSR might be due to: i) higher infestations of weeds and nematodes, ii) occasional/intermittent moisture stress since rice is generally grown under aerobic conditions, iii) insufficient knowledge of water and nutrient management, and iv) higher spikelet sterility. Consequently, the yield of the aerobic rice is generally lower than puddled transplanted rice (Gathala et al., 2011; Das et al., 2020). However, the significant relationships of SQI with REY and MY are useful for predicting crop yields corresponding to the given changes in SQI.

4. Conclusion

This study revealed that medium term conservation agriculture practice (here 8 years) significantly improved soil fertility with better soil biological and physical health parameters in the topsoil and in the 5–15 cm soil layers. This confirms the first hypothesis. The plots under triple zero till rice –mustard-mungbean system with retentions of whole mungbean residue, and 40 % residues of rice and mustard [~ZTDSR-ZTM-ZTSMB (+R)] led to highest soil quality index (SQI), followed by the ZTDSR + BM – ZTM(+R) plots. Addition of legume residue (namely, mungbean and *Sesbania*) along with rice and mustard residues over the years improved soil quality. Key soil quality indicators identified for surface and sub-surface soil layers in Inceptisols were saturated hydraulic conductivity (physical indicator), pH; total N, available P and K (chemical indicators). These indicators can be used for early warning of the changes in soil quality, however, these being soil specific, should be used with a caution. Besides, three quantitative predictive relationships were established between rice equivalent yield and SQI; rice yield and SQI and mustard yield and SQI. In future, the yield prediction can be made with the change in soil quality from these relationships, except for the rice yield and SQI. Hence, all these key indicators should be periodically monitored along with the routine soil test to highlight the changes in soil quality, whether positive or negative. Therefore, this CA-based ZTDSR – ZTM –ZT SMB (+R) system with three crops' residue retention can be a promising crop management practice under the rice-mustard cropping system in the north-western Indo-Gangetic Plains of India and in similar agro-ecologies of the tropics and sub-tropics. This practice would lead to maintain higher soil quality index as well.

Declaration of Competing Interest

The authors report no declarations of interest.

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References

Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable systems in Northern California. Agric. Ecosyst. Environ. 90, 25–45.

Arias, M.E., Gonzalez-Perez, J.A., Gonzalez-Vila, F.J., Ball, A.S., 2005. Soil health - a new challenge for microbiologists and chemists. Int. Microbiol. 8, 13–21.

Askari, M.S., Holden, N.M., 2015. Quantitative soil quality indexing of temperate arable management systems. Soil Tillage Res. 150, 57–67.

Baghel, J.K., Das, T.K., Rana, D.S., Paul, S., 2018. Effect of weed control on weed competition, soil microbial activity and rice productivity in conservation agriculture-based direct-seeded rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. Indian J. Agron. 63 (2), 129–136.

Bhaduri, D., Purakayastha, T.J., 2014. Long-term tillage, water and nutrient management in rice–wheat cropping system: assessment and response of soil quality. Soil Tillage Res. 144, 83–95.

Bhattacharyya, P., Pal, R., Chakrabarti, K., Chakraborty, A., 2004. Effect of composting on extractability and relative availability of heavy metals present in Calcutta municipal solid waste. Arch. Agron. Soil Sci. 50, 181–187.

Bhattacharyya, R., Ved-Prakash, R.B., Kundu, S., Gupta, H.S., 2006. Effects of tillage and crop rotations on pore size distribution and soil hydraulic conductivity in sandy clay loam soil of the Indian Himalayas. Soil Tillage Res. 86, 129–140. https://doi.org/10.1016/j.still.2005.02.018.

Bhattacharyya, P., Roy, K.S., Neogi, S., Chakravorti, S.P., Behera, K.S., Das, K.M., Bardhan, S., Rao, K.S., 2012. Effect of long-term application of organic amendment in relation to global warming potential and biological activities in tropical flooded soil planted to rice. Nutr. Cycl. Agroecosyst. 94, 273–287.

Bhattacharyya, R., Das, T.K., Pramanik, P., Ganeshan, V., Saad, A.A., Sharma, A.R., 2015. Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. Eur. J. Agron. 70, 11–21.

Bhattacharyya, R., Das, T.K., Das, S., Dey, A., Patra, A.K., Agnihotri, R., Ghosh, A., Sharma, A.R., 2019. Four years of conservation agriculture affects topsoil aggregate associated ^{15}nitrogen but not the ^{15}nitrogen use efficiency by wheat in a semi-arid climate. Geoderma 337, 333–340.

Bhattacharyya, R., Chandra, S., Singh, R.D., Kundu, S., Srivastva, A.K., Gupta, H.S., 2007. Long-term farmyard manure application effects on properties of a silty clay loam soil under irrigated wheat–soybean rotation. Soil Tillage Res. 94, 386–3961.

Biswas, S., Hazra, G.C., Purakayastha, T.J., Saha, N., Mitran, T., Singha Roy, S., Basak, N., Mandal, B., 2017. Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under diff ;erent soil orders. Geoderma 292, 34–48.

Black, G.R., Hartge, K.H., 1971. Methods of soil analysis - part 1: bulk density. Agronom. Monogr. 363–375. ASA and SSA, Madison WIP.

Bradford, J.M., Peterson, G.A., 2000. Conservation Tillage. Handbook of Soil Science, pp. 247–270.

Brejeda, J.J., Moorman, T.B., Karlen, D.L., Dao, T.H., 2000. Identification of regional soil quality factors and indicators in Central and southern high plains. Soil Sci. Soc. Am. J. 64, 2115–2124.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De, Deyn, G, De, Goede, R., 2018. Soil quality A critical review. Soil Biol. Biochem. 120, 105–125.

Carter, M.R., 1992. Influence of reduced tillage systems on organic matter, microbial biomass, macro-aggregate distribution and structural stability of the surface soil in a humid climate. Soil Tillage Res. 23, 361–372.

Castellini, M., Fornaro, F., Garofalo, P., Giglio, L., Rinaldi, M., Ventrella, D., Vitti, C., Vonella, A.V., 2019. Effects of no-tillage and conventional tillage on physical and hydraulic properties of fine textured soils under winter wheat. Water 11, 484. https://doi.org/10.3390/w11030484.

Chauhan, B.S., Mahajan, G., Sardana, V., Timsina, J., Jat, M.L., 2012. Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. Adv. Agron. 117, 315–369.

Choudhary, M., Jat, H.S., Datta, A., Yadav, A.K., Sapkota, T.B., Mondal, S., Meena, R.P., Sharma, P.C., Jat, M.L., 2018. Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. Appl. Soil Eco. 126, 189–198.

Dam, R.F., Mehdi, B.B., Burgess, M.S.E., Madramootoo, C.A., Mehuys, G.R., Callum, I.R., 2005. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil Tillage Res. 84 (1), 41–53.

Das, T.K., 2008. Weed Science: Basics and Applications, first ed. Jain Brothers Publishers, New Delhi. 901p.

Das, T.K., Bandyopadhyay, K.K., Bhattacharyya, R., Sudhishri, S., Sharma, A.R., Behera, U.K., Saharawat, Y.S., Sahoo, P.K., Pathak, H., Vyas, A.K., Gupta, H.S., Gupta, R.K., Jat, M.L., 2016. Effects of conservation agriculture on crop productivity and water use efficiency under an irrigated pigeonpea-wheat cropping system in the western Indo-Gangetic Plains. J. Agric. Sci. (Cambridge) 154 (8), 1327–1342.

Das, T.K., Saharawat, Y.S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K.K., Sharma, A.R., Jat, M.L., 2018. Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. Field Crops Res. 215, 222–231.

Das, T.K., Nath, C.P., Das, S., Biswas, S., Bhattacharyya, R., Sudhishri, S., Raj, R., Singh, B., Kakralia, S.K., Rathi, N., Sharma, A.R., Dwivedi, B.S., Biswas, A.K., Chaudhari, S.K., 2020. Conservation agriculture in rice-mustard cropping system for five years: impacts on crop productivity, profitability, water-use efficiency, and soil properties. Field Crops Res. 250, 107781.

Dey, A., Dwivedi, B.S., Bhattacharyya, R., Datta, S.P., Meena, M.C., Das, T.K., Singh, V. K., 2016. Conservation agriculture in a rice-wheat cropping system on an alluvial soil of north-western Indo-Gangetic plains: effect on soil carbon and Nitrogen pools. J. Ind. Soc. Soil Sci. 64, 246–254.

Dey, A., Dwivedi, B.S., Bhattacharyya, R., Datta, S.P., Meena, M.C., Jat, R.K., Singh, R.G., 2020. Effect of conservation agriculture on soil organic and inorganic carbon sequestration, and their lability: a study from a rice-wheat cropping system on a calcareous soil of eastern Indo-Gangetic Plains. Soil Use Manag. https://doi.org/10.1111/sum.12577.

Dick, R.P., Breakwell, D.P., Turco, R.E., 1996. Soil Enzyme Activities and Biodiversity Measurements and Integrative Microbiological Indicators. Soil Science Society of America. Methods for Assess, 49, Special Publication.

Dorneles, P., Lisboa, B.B., Abichequer, A.D., Bissani, C.A., Meurer, E.J., Vargas, L.K., 2015. Tillage, fertilization systems and chemical attributes of a Paleudult Evelyn. Soils Plant Nutr. 72 (2) https://doi.org/10.1590/0103-9016-2013-0425.

Du Preez, C.C., Steyn, J.T., Kotze, E., 2001. Long-term effects of wheat residue management on some fertility indicators of a semiarid Plinthosol. Soil Tillage Res. 63, 25–33.

Franzluebbers, A.J., Hons, F.M., 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. Soil Tillage Res. 39 (3), 229–239.

Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research. International Rice Research Institute, Los Banos, Philippines, pp. 627.

Govaerts, B., Fuentes, M., Mezzalama, M., Nicol, J.M., Deckers, J., Etchevers, J.D., Figueroa-Sandoval, B., Sayre, K.D., 2007a. Infiltration, soil moisture, root rot and nematode populations after 12 years of diff ;erent tillage, residue and crop rotation managements. Soil Tillage Res. 94, 209–219.

Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K.D., Luna-Guido, M., Vanherck, K., Dendooven, L., Deckers, J., 2007b. Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl. Soil Ecol. 37, 18–30.

Gupta, D.K., Bhatia, A., Das, T.K., Singh, P., Kumar, A., Jain, N., Pathak, H., 2015. Economic analysis of different greenhouse gas mitigation technologies in rice-wheat cropping system of the Indo-Gangetic Plains. Curr. Sci. 110 (5), 867–874.

Gupta, D.K., Bhatia, A., Kumar, A., Das, T.K., Jain, A., Tomer, R., Malyan, S.K., Fagodiya, R.K., Dubey, R., Pathak, H., 2016. Mitigation of greenhouse gas emission from rice–wheat system of the Indo-Gangetic plains: through tillage, irrigation and fertilizer management. Agric. Ecosyst. Environ. 230, 1–9.

Haynes, R.J., 1999. Size and activity of the soil microbial biomass under grass and arable management. Biol. Fertil. Soils 30, 210–216.

Hazra, B., Chandra, M., 2016. Plasmon hybridization mediated structure-specific refractive index sensitivity of hollow gold nanoprism in the Vis-NIR Region. ACS Sens. 1 (5), 536–542.

Jackson, M.L., 1967. Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi.

Jat, S.L., Parihar, C.M., Dey, A., Nayak, H.S., Ghosh, A., Parihar, N., Singh, A.K., 2019. Dynamics and temperature sensitivity of soil organic carbon mineralization under medium-term conservation agriculture as affected by residue and nitrogen management options. Soil Tillage Res. 190, 175–185.

Kaiser, H.F., 1960. The application of electronic computers to factor active soil organic matter pools. Soil Sci. Soc. Am. J. 58, 1130–1139.

Kumawat, C., Sharma, V.K., Meeana, M.C., Dwivedi, B.S., Barman, M., Kumar, S., Chobe, K.A., Dey, A., 2018. Effect of crop residue retention and phosphorous fertilization on P use efficiency of maize (Zea mays) and biological properties of soil under maize-wheat (Triticum aestivum) cropping system in an Inceptisol. Indian J. Agric. Sci. 88, 1184–1189.

Lal, B., Gautam, P., Panda, B.B., Raja, R., Singh, T., Tripathi, R., 2017. Crop and varietal diversification of rainfed rice based cropping systems for higher productivity and profitability in Eastern India. PLoS One 12 (4), e0175709.

Li, L.L., Huang, G.B., Zhang, R.Z., Bill, R., Guangdi, L., Kwong, Y.C., 2011. Benefits of Conservation agriculture on soil and water conservation and its progress in China. Agric. Sci. China 10, 850–859.

Lindsay, W.L., Norvell, W.A., 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci. Soc. Am. J. 42, 421–428.

Lou, W., 2002. Evaluation and prediction of soil quality based on artificial neural network in the Sanjiang Plain. Chin. J. Manag. Sci. 10, 79–83.

Mandal, B., Majumder, B., Adhya, T.K., Bandyopadhyay, P.K., Gangopadhyay, A., Sarkar, D., Kundu, M.C., GuptaChoudhury, S., Hazra, G.C., Kundu, S., Samantaray, R.N., Misra, A.K., 2008. The potential of double-cropped rice ecology to conserve organic carbon under subtropical climate. Glob. Change Biol. 14, 1–13.

Manjaiah, K.M., Singh, D., 2001. Soil organic matter and biological properties after 26 years of maize-wheat-cowpea cropping as aff ;ected by manure and fertilization in a cambisol in semi-arid region of India. Agric. Ecosyst. Environ. 86, 155–162.

Meean, M.C., Dwivedi, B.S., Mahala, D., Das, S., Dey, A., 2018. Nutrient dynamics and management under conservation agriculture. In: Singh, V.K., Gangwar, B. (Eds.), System Based Conservation Agriculture. Westville Publishing House, New Delhi, p. 43.

Merrington, G., Nfa, L.W., Parkinson, R., Redman, M., Winder, L., 2004. Agricultural Pollution: Environmental Problems and Practical Solutions. CRC Press.

Mohammad, A., Sudhishri, S., Das, T.K., Singh, M., Bhattacharyya, R., Dass, A., Khanna, M., Sharma, V.K., Dwivedi, N., Kumar, M., 2018. Water balance in direct-seeded rice grown under a conservation agriculture-based rice-mustard cropping system in North-western Indo-Gangetic Plains of India. Irrig. Sci. 36, 381–393.

Mukherjee, A., Lal, R., 2014. Comparison of soil quality index using three methods. PLoS One 9 (8) e105981.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L. (Ed.), Methods of Soil Analysis. Part 2. Agronomy Monographs 9.ASA and SSSA, Madison. WI, pp. 539–579.

Olsen, S.R., Cole, C., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Cric. U. S. Dept. Agric. 939.

Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), 1982. Methods of Soil Analysis. Part-2. Soil Sci. Soc. Am. J. Madison, Wisconsin, USA.

Page, K.L., Dang, Y.P., Dalal, R.C., 2020. The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. Front. Sustain. Food Syst. 4 (31), 1–17.

Parihar, C.M., Singh, A.K., Jat, S.L., Dey, A., Nayak, H.S., Mandal, B.N., Saharawat, Y.S., Jat, M.L., Yadav, O.P., 2020. Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. Soil Tillage Res. 202, 104653.

Parker, D.R., Gardner, E.H., 1981. The determination of hot water soluble boron in some acid Oregon soils using a modified azomethine-H procedure. Commun. Soil Sci. Plant Anal. 12, 1311–1322.

Paz-Kagan, T., Shachak, M., Zaady, E., Karnieli, A., 2014. A spectral soil quality index (SSQI) for characterizing soil function in areas of changed land use. Geoderma 230, 171–184.

Pheap, S., Lefevre, C., Thoumazeau, A., Leng, V., Boulakia, S., Koy, R., 2019. Multi-functional assessment of soil health under Conservation Agriculture in Cambodia. Soil Tillage Res. 194, 104349 https://doi.org/10.1016/j.still.2019.104349.

Piegholdt, C., Geisseler, D., Koch, H.J., Ludwig, B., 2013. Long-term tillage effects on the distribution of phosphorus fractions of loess soils in Germany. J. Plant Nutri. Soil Sci. 176, 217–226.

Rathore, L., Pal, A.R., Sahu, K.K., 1999. Tillage and mulching effects on water use, root growth and yield of rainfed mustard and chickpea grown after lowland rice. J. Sci. Food Agric. 78 (2), 149–161.

Reynolds, W.D., Elrick, D.E., 1991. Determination of hydraulic conductivity using a tension infiltrometer. Soil Sci. Soc. Am. J. 55, 633–639.

Reynolds, W.D., Elrick, D.E., Youngs, E.G., Amoozegar, A., Booltink, H.W.G., Bouma, J., 2002. Saturated and field-saturated water flow parameters. In: Dane, J.H., Topp, G. C. (Eds.), Methods of Soil Analysis. Part 4. Physical methods. SSSA, Madison, WI, pp. 797–878.

Salomé, C., Coll, P., Lardo, E., Metay, A., Villenave, C., Marsden, C., Blanchart, E., Hinsinger, P., Le Cadre, E., 2016. The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: a case study in Mediterranean vineyards. Ecol. Indic. 61, 456–465.

Schoenholtz, S.H., Miegroet, Van., Burger, J.A., 2000. A review of chemical and physical properties as indicators of forest quality: challenges and opportunities. For. Ecol. Manag. 138, 335–356.

Sen, S., Kaur, R., Das, T.K., Shivay, Y.S., Sahoo, P.M., 2018. Bio-efficacy of sequentially applied herbicides on weed competition and crop performance in dry direct-seeded rice (*Oryza sativa*). Indian J. Agron. 63 (2), 230–233.

Shahid, M., Nayak, A.K., Shukla, A.K., Tripathi, R., Kumar, A., Mohanty, S., Bhattacharyya, P., Raja, R., Panda, B.B., 2013. Long-term effects of fertilizer and manure applications on soil quality and yields in a sub-humid tropical rice-rice system. Soil Use Manag. 29, 322–332.

Sharma, K.L., Uttam Kumar, M., Srinivas, K., Vittal, K.P.R., Mandal, B., Kusuma Grace, J., Ramesh, V., 2005. Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. Soil Tillage Res. 83, 246–259.

Sharma, K.L., Grace, J.K., Mandal, U.K., Gajbhiye, P.N., Srinivas, K., Korwar, G.R., Bindu, V.H., Ramesh, V., Ramachandran, K., Yadav, S.K., 2008. Evaluation of long-term soil management practices using key indicators and soil quality indices in a semi-arid tropical alfisol. Soil Res. 46, 368–377.

Singh, B., Chanasyk, D.S., Mcgill, W.B., Nyborg, M.P.K., 1994. Residue and tillage management effects on soil properties of typic Cryoboroll under continuous barley. Soil Tillage Res. 32, 117–133.

Six, J., Connant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-sequestration of soils. Plant Soil 241, 155–176.

Spedding, T.A., Hamel, C., Mehuys, G.R., Madramootoo, C.A., 2004. Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. Soil Biol. Biochem. 36, 499–512.

Susha, V.S., Das, T.K., Nath, C.P., Pandey, R., Paul, S., Ghosh, S., 2018. Impacts of tillage and herbicide mixture on weeds interference, agronomic productivity and profitability of a maize–wheat system in the North-western Indo-Gangetic Plains. Field Crops Res. 219, 180–191.

Takoutsing, B., Weber, J., Aynekulu, E., Martín, J.A.R., Shepherd, K., Sila, A., Diby, L., 2016. Assessment of soil health indicators for sustainable production of maize in smallholder farming systems in the highlands of Cameroon. Geoderma 276, 64–73.

Tisdale, S.L., Nelson, W.L., Beaton, J.D., Havlin, J.L., 1993. Soil Fertility and Fertilizers. Macmillan, New York, pp. 176–229.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass carbon. Soil Biol. Biochem. 19, 703–707.

Walkley, A., Black, A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. Soil Sci. 37, 29–38.

Yoder, R.E., 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. Agron. J. 28, 337–351.