



Research article

Assessment of soil health parameters and application of the sustainability index to fields under conservation agriculture for 3, 6, and 9 years in India

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ABSTRACT

The effect of duration of conservation agriculture adoption on soil carbon dynamics and system sustainability was evaluated on farms of 30 villages in the Nilokheri block of Karnal district, Haryana, India. Sustainability was evaluated, in which a number of soil physical, chemical, and biological parameters were measured and a Sustainability Index (SI) was applied. Soil samples were collected from existing conservation agriculture (CA) and conventional tillage (CT) farms. Villages under CA practices were subdivided as CA3, CA6, and CA9 based on the number of years of CA practice adoption. Results showed that bulk density (BD) of 0–15 cm soil depth was 7% greater in CA3 plots, whereas in CA6 and CA9 plots BD values were only 2% and 3% higher than CT. Soil organic carbon (SOC) in 0–15 cm soil depth was found to be greater by 16.32% in CA3 than CT plots, whereas SOC was higher by 38.77% and 61.22% in CA6 and CA9. In CA, for the 0–15 and 15–30 cm soil depths, labile pools were 36% and 22% greater than CT, respectively. For both the soil depths in CA, the recalcitrant pool was 12% and 9% more than CT, respectively. Microbial biomass carbon (MBC) values of the 0–15 cm soil depth were increased over CT by 18.57%, 47.08%, and 71.5% for CA3, CA6, and CA9 respectively. In CA plots, the SI of 0–15 cm soil depth ranged between cumulative ratings (CR) of 18–21, which indicates that CA practice is “sustainable” for both soil depths. For CT, CR ranged from 25 to 30 for both soil depths resulting in a SI of “sustainability with high input”. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) scores showed that SOC had the maximum weight (0.96) towards sustainability, giving it a rank of 1. Effective rooting depth (ERD), BD, texture, and wilting point (WP) ranked 2, 3, 4 and 5, respectively, indicating their corresponding weight of contribution towards the SI. Farmers in the Karnal district should be encouraged to adopt CA practices as they can increase SOC and move the systems from “sustainable with high input” to “sustainable”.

1. Introduction

Soil is a vital natural resource. The biological, chemical, and physical processes that occur within the soils are profoundly complex. Therefore, understanding and predicting the changes in a soil system following the alterations due to agricultural practices are very difficult. The state of the processes and mechanisms in a particular soil is called “soil health”, which is the ability of a soil to function as an important ecosystem. In the concept of soil health (formerly soil quality), soil is considered as an ecosystem, where a soil system can be managed to be more “healthy” [1]. A healthy soil is also more sustainable, provides nutrients for plants,

captures and retains water, and provides a more robust habitat for microorganisms than an “unhealthy” soil [2, 3, 4]. Conventional tillage (CT) being highly intensive in nature and their continuous use in crop production, causes several agricultural challenges such as water and labour crises, extended land degradation [5], loss of SOC through accelerated oxidation [6], and increases greenhouse gas (GHG) emissions [7], promotes loss of vital plant available nutrients [8], poor soil health [9], and agricultural sustainability [10]. Global degradation of soils has risen to the level of an existential threat, and now presents a challenge for scientists to develop advanced soil conservation practices for sustainable productivity [20] and improved soil health. In this context, conservation

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agriculture (CA) has evolved as a response to concerns of agricultural sustainability on a global scale. Worldwide coverage of CA practices is ~8 % of the world arable land (124.8 M ha) [11]. In India, CA adoption is still in the initial phases [12]. Over the past few years, adoption of zero tillage and CA has expanded to cover about 1.5 million hectares [13]. According to FAO (2012), CA is applicable to all “agricultural landscapes and land uses with locally adapted practices” [11]. Managing agro-ecosystems for sustainably improved productivity, better profits, and food security, while safeguarding the environment and improving natural resources are hallmarks of CA. Conservation agriculture practices is proved to improve soil health [14], soil organic carbon (SOC) [15], soil hydraulic properties [16], root water uptake [9], ecosystem services [17], conserve soil moisture [18], and reduces the water footprints [18, 19]. Several studies reported the yield benefits under CA [20], many have reported at par yield with CT [21] while few have reported that in the initial years of adoption there was no change of yield under CA [22]. Indeed, in many situations, increases in yield may not come in the early years, if at all. For this reason, benefits other than yield increases are required for proper evaluation. But there is a lack of quantitative recommendations for and reliable assessments of the effect of conservation agricultural practices over the short and/or long terms. Also, assessment of agricultural sustainability of fields under CA is very much important.

An important criterion for sustainable production systems is the maintenance of an environment in the root-zone that optimizes soil microbial ecological diversity [23], including healthy root functions to the maximum possible depth. Roots are thus able to function effectively to capture plant nutrients and water, and to also interact with a range of soil microorganisms beneficial for plant performance [24, 25]. If adoption of recommended CA practices is to continue to increase, research in CA must have longer term perspectives, as well as reliable and repeatable assessments to describe progress and/or success.

Lal (1994) proposed a system of measurements to semi-quantify the effects of CA practices on agricultural soil systems through an index of sustainability [26]. The components of sustainability can be weighted and a cumulative rating (CR) can be applied. Through this approach, agricultural systems of practices can be assessed for progress along a CA sustainability continuum, and different systems may be compared for their relative sustainability. Maintenance or improvement of soil organic matter content, biotic activity, soil structure, and water dynamics are critical indicators for sustainable production and natural resource protection.

In this study, CA practices were carried out in different areas under different time spans ranging from short term (3 years) to long term (9 years). Different soil health indicators were measured according to Lal (1994) [26] to aid in the quantification of the effect of CA practices. These included aggregate stability, mean weight diameter (MWD), bulk density (BD), organic carbon (OC), different carbon pools and indices, glomalin content, and microbial biomass activity. Our hypothesis was that SI and CR proposed by Lal (1994) [26] could be used to quantify the state of progress in CA systems of different ages compared to CT systems.

2. Methods

2.1. Study site characteristics

The study was conducted in Nilokheri block of Karnal district, Haryana, India (Figure 1). The climate of the district is characterized by dry air with intense hot summers and cold winters. The area has a subtropical continental monsoon climate. The summer monsoon arrives at the end of June and the southwest monsoon prevails from July to September. There are substantial variations in temperature, and dry air predominates for the majority of the year. The average annual rainfall (2013–2019) of the district was 795 mm with mean 47 rainy days each year. The year 2018 experienced around 1300 mm of rainfall. The average minimum and

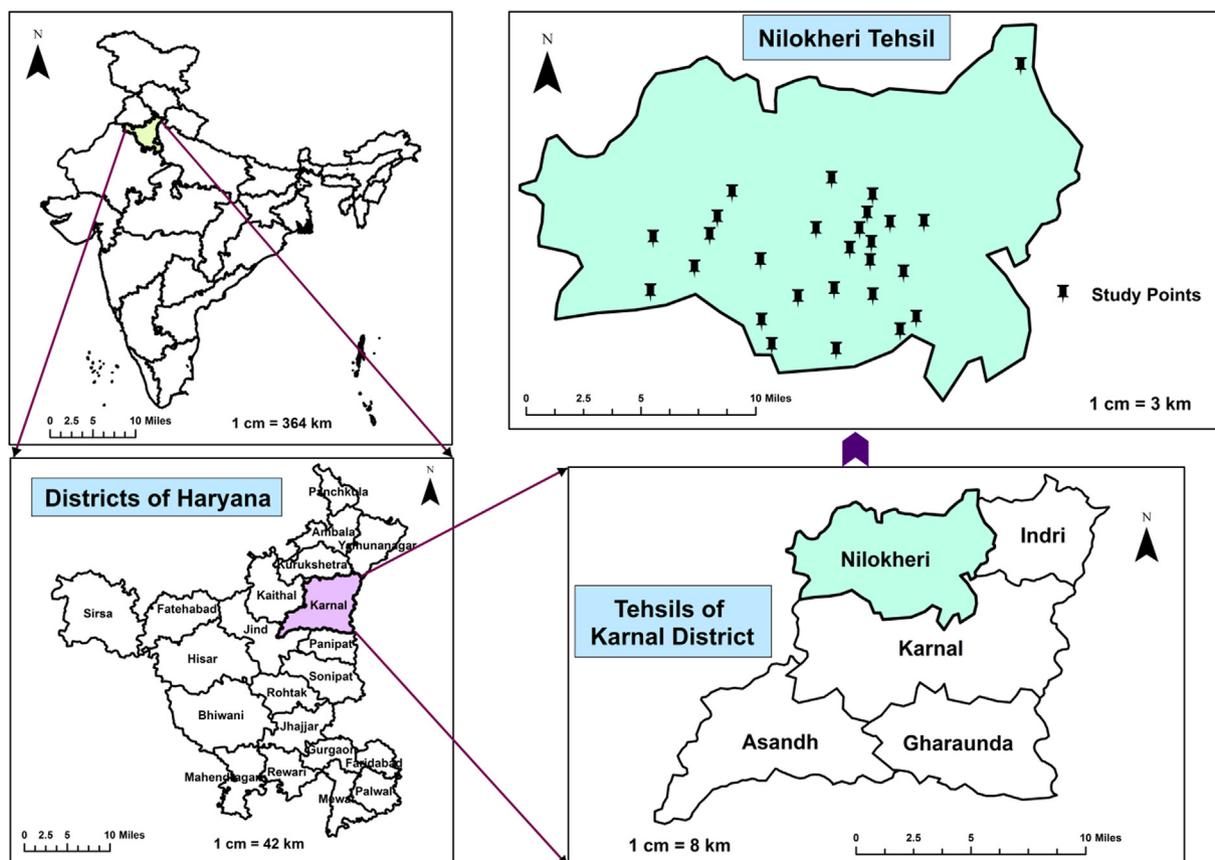


Figure 1. Location of sampling points.

Table 1. Details of the management history of the study area.

Season	Cropping history	Name of crops	Method of cultivation	Year of adoption	Varieties	Duration (days)	Area Grown (hectare)	Yield (t/ha)	
<i>Kharif</i>	Rice- wheat	Rice	Transplanted	Traditional method	Pusa 1121	125	Total area under transplanted rice	5	
<i>Rabi</i>		Wheat	Zero tillage with residue	2009	HD2937	140	20-25% area under CA	4.9	
Fertilizer and residue management									
Name of crops	N source	Amount of residue/organic amendment applied	N dose (kg ha ⁻¹)	P source	P dose (kg ha ⁻¹)	K source	K dose (kg ha ⁻¹)	Depth of irrigation water applied (cm)	Source of irrigation water
Rice	DAP, Urea	-	120	DAP	40	MOP	40	6	Tubewell
Wheat	DAP, Urea	20-30% surface was covered with residue	120	DAP	40	MOP	40	6	Tubewell

maximum air temperatures, 6.2 and 36.1 °C were recorded for the month of January and June, respectively. The soil of the study area belongs to the major group of Indo-Gangetic Alluvium. The texture is varying from sandy clay loam and clay loam. The soil belongs to the order Entisol, suborder fluvents, and great group Ustifluvents.

2.2. Treatments and experimental design

During the field visit, 140 villagers were interviewed in 30 villages of Nilokheri block of Karnal district for the purpose of collecting data regarding method of cultivation, cropping history, variety used, average yield, depth and source of irrigation water, amount and type of fertilizers applied (Table 1). The survey revealed that the number years of practicing CA varied in different villages. Based on the information generated through survey, 30 villages were divided into three groups: CA3, CA6 and CA9 according to the number of years of CA adoption. The study area was under continuous rice (in *kharif* season)-wheat (in *rabi* season). The rice was puddled transplanted and wheat was sown by drill seeding in zero-till conditions and residues were retained on the soil surface. The area of the 30 villages varied from 121- 2055 ha. Soil samples were collected from both CA and CT fields in each village during the wheat growing season (February and March, 2019) from the 0-15 cm and 15-30 cm soil depths. In each village, 6–7 soil samples were collected from the field under CA and one composite sample was made for that village. Similar sampling procedure was followed for CT. A total 60 soil samples were collected from CT and CA fields from both the soil layers. For analysis of different parameters, the soil samples were air dried outdoor under shade, ground with wooden pestle and mortar, and stored in plastic bottles (50 ml with plastic screw type lids).

2.3. Measurement of soil parameters

Soil BD was measured using the core auger method [27]. The core method is recommended for soil BD measurement when fragments are coarse and occupy less than 25% by volume. Coarse particles are those greater than 2 mm in diameter. A core cutter of 5.5 cm diameter and 15 cm height was used. In this method, a double cylinder drop hammer sampler with a core is designed to take out a cylindrical core of soil. The soil core was oven dried at 105 °C for 18–24 h and was then weighed. Bulk density was obtained by dividing the weight of the soil with volume of the apparatus core.

BD was calculated by the following equation (Eq. 1).

$$BD \text{ (Mgm}^{-3}\text{)} = \frac{(X - Y)}{V} \quad (1)$$

Where, X = Weight of core with oven dry soil (g)

$$Y = \text{Weight of core (g); } V = \text{Volume of core (cm}^3\text{)} = 117.75 \text{ cm}^3$$

Aggregate analysis was done according to the procedure recommended by Six (2004) [28]. Air dried soil samples were broken gently with hand, and then passed through a sieve of 8 mm. The soils that passed through 8 mm but remained on a 4 mm sieve were collected. The aggregate size distribution was assessed using the Yoder wet sieving apparatus. Air dried samples (100 g) were sub-sampled. The soil sample was spread evenly on top of 2 mm sieve followed by a nest of sieves with openings of 2 mm, 0.25 mm, 0.053 mm, and a collection pan. The sieves were lowered into the water so that the sample in the top sieve was just covered with water in the upstroke of the apparatus. The sieves were raised and lowered 30 times over a period of 10 min in water.

Mean weight diameter (MWD) of the aggregates was calculated using the equation (Eq. 2).

$$MWD = \sum xi wi \quad (2)$$

Where xi is the mean diameter of i^{th} class (mm), wi is the weight of i^{th} class

Soil total organic carbon (TOC) was measured with the help of a TOC analyzer (Vario TOC Select, 2011 Elementar, Germany). The carbon dioxide liberated by heating the soil sample at 700 °C was measured by a non-dispersive infrared sensor. Oxidizable SOC was determined using the wet oxidation method proposed by [29]. To extract different pools of SOC, increasing oxidizing condition was imposed through a modified Walkley and Black procedure as described by Chan et al. (2001) [30]. Briefly, 12.0 N, 18.0 N, and 24.0 N H₂SO₄ were used to separate TOC into four different pools according to their decreasing order of stability [30] and decreasing capacity for oxidation.

Pool I (very labile): Amount of organic carbon oxidized by 12.0 N H₂SO₄.

Pool II (labile): The difference in amount of carbon oxidized by 18N and that by 12.0 N H₂SO₄.

Pool III (less labile): The difference in amount of carbon oxidized by 24.0 N and that by 18.0 N H₂SO₄.

Pool IV (non labile): The difference in total carbon and carbon oxidized by 24.0 N

Labile fraction = Pool I + Pool II

Non labile/ Recalcitrant fraction = Pool III + Pool IV

Indices calculated:

Lability Index (LI): A lability index for SOC was calculated as the ratio of lability of carbon obtained in soil sample to the lability of carbon in reference soil (conventionally tilled plots). Lability of carbon in each soil

sample was measured as the ratio of labile pool (very labile + labile) to non-labile pool (less labile + non labile) carbon.

Carbon Pool Index (CPI): sample total C (mg/g)/reference total C (mg/g)

Carbon Management Index (CMI): = CPI * LI * 100

2.3.1. Microbial biomass carbon (MBC)

MBC, which constitutes 1-5% of total carbon, was determined by Fumigation-extraction method [31]. The microorganisms in the soil sample were terminated by overnight fumigation with chloroform. Both fumigated and refrigerated non-fumigated soil samples were digested using 0.2 N $K_2Cr_2O_7$, concentrated H_2SO_4 , and orthophosphoric acid (H_3PO_4). After adding a ferroin indicator, the contents were titrated using 0.005 N ferrous ammonium sulphate to obtain a brick red end-point. Microbial biomass carbon was calculated by the method proposed by Jeckinson and Powlson (1976) [31].

2.3.2. Dehydrogenase activity

The dehydrogenase activity was measured using the Tabatabai and Bremner (1969) method [32]. Triphenyl Tetrazolium Chloride (3% TTC) was added as 0.2 mL to 1 g air dried soil. Glucose (0.5 mL of 1% solution in water) was added and left for incubation at 28 ± 0.5 °C for 24 h. After incubation, 10 ml of methanol was added and shaken vigorously and allowed to stand for 6 h. A clear pink color liquid was extracted from the supernatant and readings were recorded with a spectrophotometer at 485 nm.

2.3.3. Acid and alkaline phosphatase activity

Acid (pH 6.5) and alkaline phosphatase (pH 11) were also measured by Tabatabai and Bremner (1969) method [32]. In this method, two sets of 1 g soil samples were taken and 0.2 ml toluene and 4 ml Modified Universal Buffer (MUB) at pH 6.5 and pH 11 were added. Additionally, 1 ml p-nitrophenyl phosphate solution was added to one of the sets and left for incubation at 37 °C for one hour. After incubation 1ml of 0.5 M $CaCl_2$ and 4 ml of 0.5 N NaOH was added and swirled for few seconds. 1 ml of p-nitrophenyl phosphate was added to the remaining sets. All suspensions were filtered through Whatmann no 2. The yellow color intensity was measured at 440 nm. Standard p-nitrophenol was used as a standard for this test. Phosphomonoesterase activity was expressed as microgram p-nitrophenol released per gram soil per hour.

2.3.4. Glomalin content

The glomalin content was determined as per Wright et al. (1998) [33]. Total glomalin (TG) was extracted from 1 g soil samples of ground dry-sieved soil with 8 mL of 20 mmol citrate (pH 7.0), and autoclaved at 121 °C for 60 min. The protein content in the supernatant was

determined by the Bradford assay [34] with bovine serum albumin as the standard on a 96-plate reader (Victor, Perkin Elmer, USA).

2.3.5. Available N, P, K

Determination of available nitrogen in soils was done by Subbiah et al. (1956) [35]. Available phosphorus in soil was determined using the method outlined by Olsen (1954) [36]. Available potassium in soil was measured by the procedure outlined by Hanway et al. (1952) [37].

2.3.6. Calculation of sustainability index (SI)

Critical limits suggested by Lal (1994) [26] were used for calculating the sustainability index (SI) for CA and CT systems. For assessing the sustainability of the CA and CT systems three villages were selected: Taraori, Gholpur and Sambi. Calculation of SI was done on the basis of 11 indicators. These included bulk density (ρ_b), effective porosity (θ_e), wilting point (WP), soil water content at 1.5 MPa, available water capacity (AWC) to 20 cm, saturated hydraulic conductivity (K_s), soil organic carbon (SOC), coarse fragment fraction (CFF) (>2 mm), effective rooting depth (ERD), electrical conductivity (EC), and soil textural class. The estimation procedure of each parameter is given in Table 2. Taking limitations to crop production into consideration, critical values for each indicator and the relative weighing factors were assigned. The SI was obtained by summing up critical values for each indicator within a depth individually for each field. Sustainability of each field was determined from the cumulative ratings (CR) proposed by Lal (1994) [26].

The scoring of each soil health indicator according to the SI was done using the TOPSIS model (Technique for Order Preference by Similarity to Ideal Solution). This is a multi-criteria decision analysis method [38]. It compares a set of alternatives by identifying weights for each criterion, and then calculates the best scores for each criterion. The basic concept of TOPSIS is that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative-ideal solution.

2.4. Statistical analysis

The statistical analyses were performed using the SPSS 20.0 statistic software package (SPSS Inc., Chicago, IL, USA). Turkey's post hoc test and least significant difference (LSD) were used to check the significant differences in variables among treatments at $\alpha=0.05$. The TOPSIS model was performed using R software (URL <http://www.R-project.org/>).

3. Results and discussion

3.1. Bulk density

Soil BD in 0-15 cm and 15-30 cm soil depths in CA and CT plots is shown in Table 3. The BD of 0-15 cm soil depth of CT, CA3, CA6, and CA9 were 1.29, 1.39, 1.32 and 1.33 Mgm^{-3} , respectively. These differences

Table 2. Various soil indicators and their estimation techniques used in determining SI.

Soil Indicator	Method of Measurement	Reference
Bulk Density	Core method	Blake & Hartge (1986)
Effective Porosity	Difference between θ at saturation and 30 kPa	-
Wilting Point	Pressure Plate apparatus	Richards (1943)
Available Water Content	Difference between θ at 30 kPa and 1500 kPa	Pressure Plate Apparatus
Saturated Hydraulic Conductivity	Constant head method	Klute & Dirksen (1986)
Soil Organic Carbon	Wet digestion	Walkley and Black (1934)
Texture	Bouyocous Hydrometer method	Bouyocous (1962)
Coarse Fragment Fraction	Particles >2mm by Aggregate analysis	Six et al. (2004)
Effective Rooting Depth	By sampling the crop roots	Aggarwal et al. (2006)
EC	Conductivity cell	Jackson (1973)
pH	pH meter	Jackson (1973)

Table 3. Effect of conventional and conservation agriculture practices on soil bulk density, soil organic carbon and soil organic carbon storage in 0–15 and 15–30 cm soil depth.

Depth (cm)	BD\$ (Mgm ⁻³)				SOC (gkg ⁻¹)				SOC Storage (MgCha ⁻¹)			
	CT#	CA 3	CA 6	CA 9	CT	CA 3	CA 6	CA9	CT	CA 3	CA 6	CA 9
0–15	1.29 ^{a†}	1.39 ^a	1.32 ^a	1.33 ^a	4.9 ^c	5.7 ^{bc}	6.8 ^{ab}	7.9 ^a	9.48 ^c	11.88 ^b	13.46 ^{ab}	15.76 ^a
15–30	1.38 ^{ab}	1.44 ^a	1.41 ^{ab}	1.33 ^b	3.7 ^b	4.3 ^b	4.9 ^b	6.5 ^a	7.65 ^c	9.28 ^b	10.36 ^{ab}	12.96 ^a
Significance	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

\$BD: Bulk density; SOC: Soil organic carbon; # CT: Conventional tillage; CA3: Conservation agriculture adopted for 3 years; CA6: Conservation agriculture adopted for 6 years; CA9: Conservation agriculture adopted for 9 years; †Treatments with different letters are significantly different at same depth, whereas bottom cell under each treatment shows significance level between depths under same treatment.

were not significant. BD values for 15–30 cm soil depths were 0.05–0.08 Mgm⁻³ higher than the 0–15 cm depth. In this study, BD was numerically lower in CT than CA plots in the 0–15 cm soil depth. However, after 9 years of CA adoption, subsurface BD was numerically less as compared to CT. An interesting trend to follow in this studies was the early slight increase in subsurface BD after three years of CA (CA3), followed by a significant decrease from 1.44 to 1.33 Mg m⁻³ by year nine. Terefe and Lemma (2016) reported that after four years of CA practices, mean BD values of soil were not significantly different between practices [39]. Several studies [40, 41, 42] conducted in Tanzania, Kenya, and Zimbabwe, separately observed that soil BD was not significantly different under CA and CT treatments within four to five years of CA adoption. However, Osunbitan et al. (2005) reported that after 8 years of CA practices, soil BD in CA was significantly lower than CT [43]. Our results suggest that soil BD may be changed or improved after practicing CA for more than four to five years of time. He et al. (2009) observed that soil BD under CA practices was higher for the initial few years [44]. Building soil organic matter and aggregate stability following transition to CA practices take a significant time to achieve the desired levels. Crop residue addition in CA plays an essential role in altering BD, as decaying plant material has a substantially lower BD than mineral matter. Decomposition of crop residue results in products which aid in the development of soil aggregation [45, 46].

3.2. Soil organic carbon

The SOC contents for the 0–15 cm soil depths under CT, CA3, CA6, and CA9 were 4.9, 5.7, 6.8, and 7.9 gkg⁻¹, respectively (Table 3). The results indicated that SOC contents were higher by 0.8, 1.9, and 3.0 g kg⁻¹, respectively for CA3, CA6, and CA9, when compared to the CT plots. The SOC values were also higher in the CA plots, but a significant increase was only observed between the CT and the CA9 treatments. The SOC contents for the 15–30 cm soil depth for CT, CA3, CA6, and CA9 were 3.7, 4.3, 4.9, 6.5 gkg⁻¹, respectively. As with the surface depths, SOC for CA9 were significantly higher than that of CT.

Schlesinger and Bernhardt (2013) stated that CT practices decrease SOC, which can decrease plant nutrient availability [47]. Consistent with

the current study, several workers reported that no-till (NT) systems and cover cropping will potentially add organic matter to soil, which improves physical structure [48], promotes biological activity [49], and increases the pool for C and nutrient cycling [50]. Integrating management practices such as no till and cover crops in the agriculture results in a positive effect on the soil physical and biological properties of soil making the soil system more dynamic [51]. Reduced tillage systems have been found to increase SOM storage and improve nutrient cycling compared to normal tillage [52, 53]. Some workers have reported that SOC was unaltered by CA within four years of adoption [54, 55]. On the other hand, in two distinct studies conducted by Nyamadzawo et al. (2008) [56] and Gwenzi et al. (2009) [41], SOC was greater under CA after five and ten years of adoption, respectively. They explained that low SOC content in continuously cultivated soils of CT was due to lower inputs of organic matter through crop residue return, and loss from rapid organic matter oxidation promoted by frequent tillage. Tripathi et al. (2015) reported that under CA practices, residue retention with no nitrogen input improved SOC content of soil up to 14.2% over practices without residue retention [57]. In CA systems, stubble from the previous crop is left on the soil surface, resulting delay in decomposition of residue than when incorporated into the soil. This also protects the soil surface from raindrop and wind disturbance, and transport [58]. These factors were possibly very useful in achieving higher SOC content in 0–15 cm soil layer of CA plots.

3.3. Soil organic carbon storage, soil organic carbon pools, lability index, carbon pool index and carbon management index

Soil carbon storage was calculated from measured SOC values for all the treatments and depths. The SOC storage was found to follow a similar trend as SOC. The storage values for CT, CA3, CA6, and CA9 in the 0–15 cm soil layers were 9.48, 11.88, 13.46 and 15.76 MgCha⁻¹, respectively (Table 3). The increase in SOC storage for CA3, CA6, and CA9 when compared to CT were 25.31, 41.98, and 66.24%, respectively. The SOC storage was significantly higher for the three CA plots when compared to CT. The 15–30 cm soil depth showed a similar trend. The values for SOC storage were 7.65, 9.28, 10.36 and 12.96 MgCha⁻¹, respectively for CT,

Table 4. Effect of conventional and conservation agriculture practices on the carbon pools of soil and carbon management indices.

Depth (cm)	SOC pools												Carbon Management indices					
	g C kg ⁻¹ dry soil																	
	Pool I\$		Pool II		Pool III		Pool IV		Labile Pool		Recalcitrant Pool		LI*		CPI		CMI	
	CT#	CA	CT	CA	CT	CA	CT	CA	CT	CA	CT	CA	CT	CA	CT	CA	CT	CA
0–15	4.74 ^{b†}	6.29 ^a	4.01 ^b	5.64 ^a	4.57 ^a	4.84 ^a	4.12 ^a	4.88 ^a	8.75 ^b	11.93 ^a	8.69 ^a	9.72 ^a	1	1.04	1	1.51	100	156.63
15–30	4.61 ^b	5.34 ^a	3.94 ^b	5.09 ^a	4.65 ^a	4.72 ^a	4.02 ^a	4.76 ^a	8.55 ^a	10.43 ^a	8.67 ^a	9.48 ^a	1	0.99	1	1.49	100	150.74
Significance	ns	*	ns	ns	ns													

\$ Pool I, Pool II, Pool III, and Pool IV represent very labile, labile, less labile and nonlabile SOC pools, respectively, as determined following Chan et al. (2001). †Treatments with different letters are significantly different at same depth, whereas bottom cell under each treatment shows significance level between depths under same treatment.

* LI: Lability index; CPI: Carbon pool index; CMI: Carbon management index; # Ct: Conventional tillage; CA: Conservation agriculture.

Table 5. Effect of conventional and conservation agriculture practices on size distribution of aggregates, macro-aggregates and micro-aggregates after 9 years of CA adoption.

Depth (cm)	Aggregate classes											
	>2mm		2–0.25mm		0.25–0.053mm		<0.053mm		Macroaggregates		Microaggregates	
	g aggregate 100g ⁻¹ dry soil											
	CT [§]	CA	CT	CA								
0-15cm	10.19 ^{b†}	15.61 ^a	21.97 ^a	23.03 ^a	20.52 ^a	22.04 ^a	47.22 ^b	38.92 ^a	32.16 ^a	38.64 ^a	20.52 ^a	22.04 ^a
15-30cm	10.11 ^a	12.2 ^a	13.32 ^b	21.13 ^a	15.24 ^b	19.78 ^a	61.3 ^b	46.71 ^a	23.43 ^b	33.33 ^a	15.24 ^b	19.78 ^a
Depthwise significance	ns	ns	*	ns	*	ns	ns	*	ns	*	ns	*

§ CA: Conservation agriculture; CT: Conventional agriculture †Treatments with different letters are significantly different at same depth, whereas bottom cell under each treatment shows significance level between depths under same treatment.

Table 6. Effect of conventional and conservation agriculture practices on MWD.

Depth (cm)	MWD [§] (mm)			
	CT [#]	CA 3yrs	CA 6yrs	CA 9yrs
0-15	0.58 ^{c†}	0.69 ^b	0.73 ^b	0.92 ^a
15-30	0.17 ^c	0.67 ^b	0.68 ^b	0.91 ^a
Significance	**	ns	ns	ns

§ MWD: mean weight diameter, †Treatments with different letters are significantly different at same depth, whereas bottom cell under each treatment shows significance level between depths under same treatment # CT: Conventional tillage; CA3: Conservation agriculture adopted for 3 years; CA6: Conservation agriculture adopted for 6 years; CA9: Conservation agriculture adopted for 9 years.

CA3, CA6, and CA9. The increase in storage was significant for all the CA plots when compared to CT (Table 3). The subsurface SOC storage differences were lower than the surface soil differences between treatments, but the differences were not significant. Table 4 shows the different pools of carbon in CA and CT plots. For 0-15 cm soil depth in CT plots, it was found that the labile pool was 0.06 gCkg⁻¹soil greater than recalcitrant pools. In the 15-30 cm soil depths, the recalcitrant pools were 0.12 gCkg⁻¹soil greater than the labile pools. In the case of CA plots, in 0-15 cm soil depth, the labile pool was 2.21 gCkg⁻¹soil more than the recalcitrant pool. In the 15-30 cm soil depths, the labile pool held 0.95 gCkg⁻¹soil more than recalcitrant pool. Results showed that in CA for 0-15 cm and 15-30 cm soil depths, labile pools were 3.18 and 1.88 gCkg⁻¹ more than CT. For both soil depths, the recalcitrant pool in CA was 12% (surface) and 9% (subsurface) more than CT.

In CA plots, the recalcitrant pool was 12 and 9% more than CT for these two depths, respectively (Table 4). Bongiorno et al. (2019) stated that labile C pools are considered more appropriate soil health indicators than total SOC as they are more sensitive to any changes in management [59]. On the other hand, the recalcitrant pool changed gradually by microbial activities [60] and played a significant role in SOC retention. Bhattacharyya et al. (2013) showed that plots under CA had 33% more labile SOC (Pool II) than CT plots (2.01 gCkg⁻¹) in the 0-15 cm soil depth [61]. Consistent with this study, Dou et al. (2008) observed that CA significantly ($p < 0.05$) improved SOC content when they compared the proportion of all labile SOC pools with the CT treatment, after 20 years of CA adoption in south-central Texas [62]. They found significantly higher labile SOC in CA at 0-15 cm only, attributing the difference to greater

biomass C. In the 0-15 cm soil depths, the LI for CA treatments increased 4% with respect to CT (Table 4). The CPI was 51% higher in CA than CT in 0-15 cm soil layer, whereas it was 49% higher in 15-30 cm soil layer of CA plots. The CMI increased 57.04% and 47.51% in 0-15 cm and 15-30 cm of soil depths under CA practices.

3.4. Size distribution of aggregates and mean weight diameter

Table 5 shows the effects of conventional and conservation agriculture practices on size distribution of total aggregates, macroaggregates, and microaggregates. It was observed that for the 0-15 cm soil depths, the CA plots had greater values (g aggregates 100 g⁻¹ dry soil) of size distribution of aggregates of class >2 mm (15.61), 2–0.25 mm (23.03), 0.25–0.053 mm (22.04), while the class size <0.053 mm had lowest values (38.92). In the surface soil, the amount of macroaggregates was greater than the microaggregates in case of both CA and CT plots. In CA, macroaggregates and microaggregates were 6.48 and 1.52 g aggregates 100 g⁻¹ dry soil higher in 0-15 cm soil layer as compared to CT. However, in the 15-30 cm soil depths, the corresponding values were greater by 9.9 and 4.54 g aggregates 100 g⁻¹ dry soil. In case of the 15-30 cm soil depths, better aggregation was observed in CA as compared to CT.

In the current study, MWD values for CT, CA3, CA6, and CA9, were 0.58, 0.69, 0.73 and 0.91 mm, respectively (Table 6). The increase in MWD (57.7%) was greatest and statistically significant for CA9 when compared with CT. Previous studies conducted in different regions also described that surface 0-15 cm soil depths under CA practices had greater aggregate MWD than soil under CT [63, 64]. Higher SOC content in the

Table 7. Effect of conventional and conservation agriculture practices on soil enzymatic activities and glomalin content in 0-15 cm soil depth.

Treatment	Dehydrogenase (µg TPF/g/hr)	Acid phosphatase (µg PNP/g/hr)	Alkaline phosphatase (µg PNP/g/hr)	Glomalin (µg/kg)
CT [#]	46.57 ^{c†}	145.83 ^b	2026.8 ^b	46.57 ^c
CA 3yrs	64.17 ^b	147.27 ^b	2058.2 ^b	52.47 ^c
CA 6yrs	65.38 ^b	165.37 ^b	2358.1 ^b	67.0 ^b
CA 9yrs	77.57 ^a	178.37 ^a	2440.7 ^a	91.0 ^a
CD (5%)	11.8	22.8	421.9	14.2

†Treatments with different letters are significantly different at same depth; # CT: Conventional tillage; CA3: Conservation agriculture adopted for 3 years; CA6: Conservation agriculture adopted for 6 years; CA9: Conservation agriculture adopted for 9 years.

0-15 cm soil depths under a CA system might have resulted in more stable macroaggregates [65]. The chemicals produced during decomposition processes and from root and endophytic fungal exudates encourage aggregation through the provision of temporary binding agents. Improved soil structure increases macroporosity, which further enhances the permeability of soil for water, air, and roots [66]. Soil aggregate loss under CT is promoted through frequent mechanical disruption and oxidation or organic matter. The stability of microaggregates is greater, and also less sensitive to soil management and tillage operations. Microaggregates are responsible for maintaining long-term stability of soil organic carbon [28]. In contrast, macroaggregates are prone to disruption through changes in the soil use and management, and are particularly linked to the dynamics of the soil organic matter [28]. Similar to our results, Zotarelli et al. (2005) reported that the MWD of aggregates was on average 0.5 mm greater under CA than CT in the 0-5 cm soil depth in Oxisols [67].

3.5. Glomalin and dehydrogenase activity

Table 7 shows the effect of CA and CT practices on the glomalin content of soil for 0-15 cm soil depths. In case of glomalin, the values for CT, CA3, CA6, and CA9 were 46.57, 52.47, 67.0, 91.0 μgkg^{-1} , respectively. The greatest glomalin content was recorded in the CA9 treatment. The difference in values of CA6 and CA9 were significant as compared to CT. The enzymatic activities under CA3, CA6, and CA9 were significantly higher than CT (Table 7). In case of dehydrogenase, CA plots showed significant increase in dehydrogenase content as compared to the CT plots. The values for CT, CA3, CA6, and CA9 were 46.57, 64.17, 65.38 and 77.57 $\mu\text{gTPF/g/hr}$, respectively. The dehydrogenase content was found to be maximum for CA9 with a percentage increase of 66.56% as compared to CT plots. The CA9 was significantly higher when compared to CT, but the difference was non-significant in case of CA3 yrs and CA6 yrs. Doran and Zeiss (2000) found that NT treatment brought about a significantly higher soil dehydrogenase activity in comparison with CT [2]. Madejon et al. (2007) and Tao et al. (2009) also observed higher dehydrogenase activity in CA [68, 69]. Parihar et al. (2016) showed that dehydrogenase in the 0-30 cm soil layers was 43.5 and 30.6% higher in zero tillage (ZT) and permanent bed (PB) treatments as compared to CT, respectively and they concluded that high dehydrogenase in CA might be due to high MBC [15]. Higher acid and alkaline phosphatase activities of soil in CA might be due to stimulation of microbial growth and soil organic matter enhancement [70]. Glomalin protein which is very important for soil aggregation [71] was significantly higher in CA as compared to CT. Singh et al. (2017) also reported that residue retained plots had 40 and 13% higher soil glomalin contents than no residue [72]. CA systems are associated with a higher arbuscular mycorrhizal fungi (AMF) diversity and enhanced functioning, while CT systems, used in the management for maximum crop production, have been shown to negatively impact AMF diversity and functioning [73, 74], thereby reducing the glomalin content of soil. Disruption of the AMF hyphal network is a proposed mechanism by which soil tillage reduces root colonization and hence nutrient absorption [75]. CT systems are often associated with low glomalin concentrations due to high turnover rates of macroaggregates to microaggregates leading to glomalin decomposition and loss [76].

3.6. Acid and alkaline phosphatase activity

The values of acid phosphatase for CT, CA3, CA6, and CA9 were 145.83, 147.27, 165.37 and 178.37 $\mu\text{gPNPg}^{-1}\text{hr}^{-1}$, respectively. The values of alkaline phosphatase were 2026.8, 2058.2, 2358.1 and 2440.7 $\mu\text{g PNPg}^{-1}\text{hr}^{-1}$, respectively. Table 7 shows that acid phosphatase activity was not significantly greater in CA3 or CA6, but in CA9 (22.3%), when compared to CT. A similar trend was found with alkaline phosphatase, where a non-significant increase of 16.3% was found for CA6

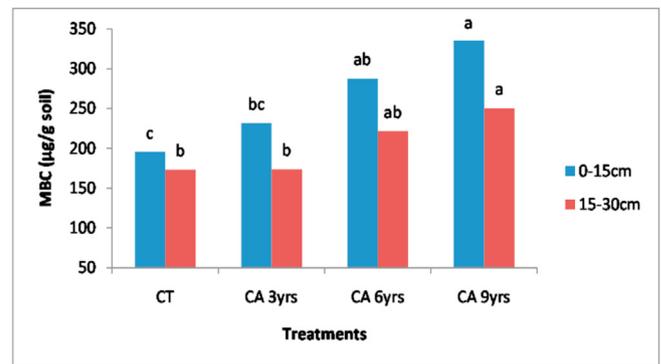


Figure 2. Effect of conventional and conservation agriculture practices on microbial biomass carbon in 0-15 and 15-30 cm soil depth (†Treatments with different letters are significantly different at same depth, whereas for CT between 0-15 cm and 15-30 cm depths were insignificant, for three other treatment depthwise significant variation was there; MBC: microbial biomass carbon; # CT: Conventional tillage; CA3: Conservation agriculture adopted for 3 years; CA6: Conservation agriculture adopted for 6 years; CA9: Conservation agriculture adopted for 9 years).

and 20.6% significant increase was observed for CA9 when compared to CT. Greater acid and alkaline phosphatase activities for soil under CA can result from stimulation of microbial growth and soil organic matter enhancement [70].

3.7. Microbial biomass carbon

Figure 2 shows soil MBC results for CT, CA3, CA6, and CA9. Soil MBC values for CT, CA3, CA6, and CA9 were 195.4, 231.7, 287.4 and 335.3 $\mu\text{gC g}^{-1}$ soil, respectively. Results showed an increase in MBC values of 0-15 cm soil depths over CT of 18.57, 47.08, and 71.5% for CA3, CA6, and CA9, respectively. A similar trend was observed in case of 15-30 cm soil depths. In CT, there was no depth-wise significant variation. In contrast, variation with depth was significant within all CA treatments. Management induced changes in soil water, temperature, and SOC influence MBC, plant nutrient availability, and SOC turnover [77]. Naveen and Babalad (2018) showed that CA practices resulted non-significantly greater MBC (335.90, 328.76, 302.40 mgkg^{-1} of soil) as compared to CT without crop residues (260.64 mgkg^{-1} of soil) [78]. They reported that over the years MBC was not significantly influenced by cropping systems, and ranged from 280.47 to 337.98 mgkg^{-1} soil. The enhancement in MBC was mainly due to rate of organic carbon input from plant biomass, which is the governing factor controlling the amount of soil microbial biomass in soil [79].

3.8. Available N, P, and K

The available N, P, and K were significantly higher in different CA treatments. Table 8 shows the available N, P and K content of soil for all the four treatments of CT, CA3, CA6, and CA9 at 0-15 cm and 15-30 cm soil depths. The available N content was found to increase significantly by 18.3, 30.84, and 70.2% in CA3, CA6, and CA9 for 0-15 cm soil depths when compared to 0-15 cm soil layers of CT. For 15-30 cm soil depths, the increase was greater in CA3 and CA9. The variation of available N in between depths was significant separately for CT and CA9 plots. For CT and CA6, the available N decreased non-significantly. Accumulation of nutrients in the soil surface layers was found due to retention of higher amounts of residue rich in plant nutrients and minimal soil disturbance, whereas under conventional practices residues were removed and remaining stubbles were thoroughly incorporated in the plough layer (0-20 cm) by tillage operations [80]. The concentration of available N under all treatments was lower than the lower limit of 260 kgNha^{-1} , which can be attributed to immobilization of inorganic N in soil [81].

Table 8. Effect of conventional and conservation agriculture practices on available N, P, K in 0–15 and 15–30 cm soil depth.

Depth	Available N (kg/ha)				Available P (kg/ha)				Available K (kg/ha)			
	CT#	CA 3yrs	CA 6yrs	CA 9yrs	CT	CA 3yrs	CA 6yrs	CA 9yrs	CT	CA 3yrs	CA 6yrs	CA 9yrs
0-15cm	115.25 ^{d†}	136.37 ^c	150.80 ^b	196.27 ^d	15.23 ^c	17.90 ^b	20.00 ^a	20.83 ^a	182.57 ^d	210.17 ^c	237.63 ^b	275.00 ^a
15-30cm	130.70 ^a	141.90 ^a	140.27 ^a	141.60 ^a	12.80 ^b	11.93 ^b	12.73 ^b	18.07 ^a	193.23 ^b	193.20 ^b	219.47 ^a	215.17 ^a
Significance	**	ns	ns	**	*	**	**	ns	ns	ns	**	**

†Treatments with different letters are significantly different at same depth, whereas bottom cell under each treatment shows significance level between depths under same treatment; # CT: Conventional tillage; CA3: Conservation agriculture adopted for 3 years; CA6: Conservation agriculture adopted for 6 years; CA9: Conservation agriculture adopted for 9 years.

Table 9. Sustainability indices for different villages under CA and CT.

Village	Cumulative Ratings		Cumulative Ratings	
	CA		CT	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
TARAORI	21	20	26	26
GHOLPUR	20	20	25	24
SAMBI	19	18	26	26

Table 10. TOPSIS Scores for various parameters used in calculating SI.

Parameters	TOPSIS Score	Rank
BD	0.44	3
EFFECTIVE POROSITY	0.22	7
WP	0.28	5
AWC	0.27	6
Ks	0.04	9
SOC	0.96	1
TEXTURE	0.42	4
CFF	0	10
ERD	0.57	2
EC	0	10
pH	0.13	8

BD: Bulk density; WP: Wilting point; AWC: Available water capacity; Ks: Saturated hydraulic conductivity; SOC: Soil organic carbon; CFF: Coarse fragment fraction; ERD: Effective rooting depth; EC: Electrical conductivity.

Results showed that in the 0-15 cm soil depths, the available P increased significantly in CA3, CA6, and CA9 by 17.7, 31.5, and 36.8%, respectively when compared to CT plots. The increase in values between CA3 and CA6 was not significant. The increase in values was significant for all the CA plots with respect to CT. The increase in available P values of CA was not significant for CA3 and CA6, but was significant for CA9 in the 15-30 cm depths. The variations for available P in between depths were significant for all treatments except CA9. Jat et al. (2018) showed that Olsen P was 25% and 38% higher under CA as compared to CT, which can be the result of higher residue retention and mineralization of organic P [80]. Du Preez et al. (2001) also reported that CA adopted for 11 years showed positive impact on available P [82]. On the other hand, Ben-Moussa et al. (2010) described that available P was similar in CA and CT plots within four years of CA in Tunisia [55].

The increase in value of available K was significantly higher in the CA plots as compared to the CT plots. The percentage increases in K in the CA plots as compared to CT were 15.11, 30.15 and 50.6%, respectively for 0-15 cm soil depths. The values of CA plots were significant for CA9 when compared to CT plots in 15-30 cm soil depth. For the same treatments the value of available K decreased with soil depth, the difference was significant in CA9. Murillo et al. (2004) and Malecka et al. (2012) showed

that the available K content of soil was significantly higher in CA plots at 0-15 cm and 15-30 cm soil depths when compared to the CT plots [83, 84]. The higher available K concentration under CA in both the soil depths may result from additions of K through crop residues.

3.9. Sustainability of CA and CT systems in different villages

Plots under CA were found to be “sustainable” in different villages, according to the application of the SI, but CT systems were “sustainable with high input”. TOPSIS scoring showed that among 11 indicators used, OC had the maximum weight (0.96) towards sustainability. The soil parameters EC, CFF, and K_s received the lowest weights. Table 9 shows the SI calculated for the villages Taraori, Gholpur, and Sambhi for both CA and CT plots at 0-15 cm and 15-30 cm soil depths. Results showed that the SI for CA plots at 0-15 cm soil depth ranged between cumulative ratings of 19–21. This indicated that the sustainability of the villages ranged from “highly sustainable” in the Sambhi village to “sustainable” in Taraori and Gholpur villages. A similar pattern was observed for 15-30 cm soil depths as well. Sambhi village showed a cumulative rating of 18 which indicated “highly sustainable” CA practice for both the soil depths. In CT, the cumulative ratings ranged from 24-26 for both the soil depths which indicated a SI of “sustainability with high input”.

Table 10 shows the TOPSIS scores of the various parameters which were used in calculating the sustainability indices. This TOPSIS score indicated the various weightage assigned to the parameters used in evaluating SI. From table it was observed that SOC had the highest score of 0.96, thus giving it rank 1. This indicates that SOC contributes maximum to sustainability. Similarly, other parameters like ERD, BD, texture, and WP ranked 2, 3, 4, and 5, respectively indicating their corresponding weight of contribution towards sustainability. The AWC and effective porosity ranked 6 and 7, respectively.

4. Conclusions

Results from the present study indicate that the SI developed by Lal (1994) [26] can be successfully used to semi-quantify the improvements in soil health and quality through the adoption of CA based cropping systems over CT systems. Soil parameters associated with soil health were often improved under CA in this study, although not always within the short term. For example, soil BD at the 0-15 cm soil depths was 7% higher in the first three years, but declined to a level below that of CT in

the 6th and 9th years. In 15-30 cm soil depths, average BD values were 3.4-6.5% higher than the surface 0-15 cm soil depths. Results showed that for 0-15 cm and 15-30 cm soil depths, the labile carbon pool were 36 and 22% greater in CA than CT. For both the soil depths, the recalcitrant carbon pool was 12 and 9% greater respectively in CA than CT. This type of assessment can be valuable in increasing farmer adoption of CA practices as it clearly demonstrates the improvements in soil physical, chemical, and biological indicators of soil health. Use of the SI in this study showed that improvements in soil health indicators can be measured in most cases by the 6th year of implementation. TOPSIS scoring showed that among 11 indicators used in this study, SOC had maximum weight or influence (0.96) towards sustainability. Future studies must tie in economic factors, such as whether a farmer stands to lose or gain net income, to the assessments of soil health indicators under CA practices in order to drive adoption more rapidly.

Declarations

Author contribution statement

Priya Bhattacharya, Pragati Pramanik Maity: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Jake Mowrer, Aniruddha Maity, Mrinmoy Ray: Analyzed and interpreted the data; Wrote the paper.

Shrila Das, Bidisha Chakrabarti, Tridiv Ghosh, P. Krishnan: Contributed analysis tools or data; Wrote the paper.

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Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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