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RESEARCH ARTICLE

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Long-term conservation agriculture helps in the reclamation of sodic soils in major agri-food systems

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Abstract

Globally crop production is impaired by soil salinity and sodicity and to maintain the sustainability of the production systems under such degraded lands, conservation agriculture (CA) may be an alternative in arid and semiarid regions. An experiment was initiated with different agri-food systems with CA-based practices to understand the reclamation potential of sodic soil after continuous cultivation for 4 and 9 years. This included: (i) conventional tillage (CT)-based rice-wheat system (Sc1); (ii) partial CA with puddled rice-zero tillage (ZT) wheat and mungbean (Sc2); (iii) ZT rice-wheat-mungbean (Sc3); (iv) ZT maize-wheat-mungbean (Sc4). Soil samples were collected from 0 to 15 and 15 to 30-cm depth after 4 and 9 years of wheat harvesting. Results showed an 18% decline in pH_2 with Sc2 and ~30% decline in EC_2 with Sc2 and Sc3 at upper soil depth after 9 years. Higher cation exchange capacity by 35% and 89% in Sc2 and 38% and 58% in Sc3 after 4 and 9 years was found, respectively, over initial levels. A decrease in exchangeable sodium percentage was recorded in Sc2 by 43% and 50%, after 4 and 9 years over the initial level, respectively. The oxidizable carbon and total organic carbon were increased by ~76%, 69%, and 64% in Sc4, Sc3, and Sc2, respectively, over initial values at 0–15 cm soil depth. Results showed that the CA-based rice-wheat-mungbean system had more reclamation potential than other studied systems. Therefore, long-term CA practices involving ZT with crop residue recycling and efficient crop rotations have the potential to reduce the sodicity stress and improve soil organic carbon thereby bringing the sodic lands under productive crop cultivation.

KEYWORDS
conservation agriculture, long-term experiment, sodicity, soil carbon pools, zero tillage

1 | INTRODUCTION

Soil salinity and sodicity are one of the major and prevalent challenges in the current era that hampers global food security and environmental sustainability in the arid and semi-arid regions of the world and adversely affect the global agricultural production and biodiversity. Globally, more than 900 million ha of land, accounting for nearly 20% of the total agricultural land and 33% of the irrigated agricultural lands is affected by salinity (Shrivastava & Kumar, 2015). The salt stress in the soil is becoming prominent due to the ever-increasing global population pressure (projected to be 9.3 billion by 2050), anthropogenic activities (e.g., intensive cultivation, over-application of groundwater and synthetic fertilizers), and climate change over decades (Mukhopadhyay et al., 2020). About 40%–60% of the World's salt-affected lands are saline and sodic in nature (Tanji, 1990). In India, the total salt-affected area is 6.74 million ha out of which approximately

2.95 and 3.79 million ha area is covered by saline and sodic soils, respectively (Sharma et al., 2015). Sodic soils are characterized by high pH (>8.5), high exchangeable sodium percentage (ESP, >15%), and low salt concentration electrical conductivity (EC, <4.0 dS m^{-1}). In India, annual losses of INR 230 billion (1USD=75 INR) occur due to the adverse effect of salinity/sodicity on crop growth and productivity (Sharma et al., 2015). This is likely to increase manifold by 2050 with a projected increase in salt-affected soils to 16.2 million ha (CSSRI Vision 2050, 2015). In India, the population is increasing day-by-day and to feed this huge (1.67 billion by 2050) population, salt-affected soils should be reclaimed and brought under productive cultivation. Moreover, at the current time, climate change together with soil salinity/sodicity will considerably affect crop productivity (Datta, Basak, et al., 2017).

Conservation agriculture (CA), having three principles of minimum soil disturbance, crop rotation, and soil cover, is endorsed as a practice for sustainable crop production that simultaneously conserves soil and water resources while reducing input costs (Jat et al., 2021; Margenot et al., 2017). The application of CA practices enhances soil quality by reducing the breakdown of soil aggregates, enhancing the infiltration rate, nutrient cycling, and soil organic carbon (SOC), which improves soil physical and biochemical properties while reducing soil erosion (Jat et al., 2018; Jat, Choudhary, et al., 2020; Jat, Datta, Choudhary, Sharma, et al., 2019; Jat, Datta, Choudhary, Yadav, et al., 2019; Zhang et al., 2018). CA practices also have higher energy-use efficiency compared to conventional tillage (CT) (Jat, Jat, et al., 2020; Rusu, 2004). The increase in SOC and aggregate stability under CA plays important role in regulating the movement of water and gas, and nutrient cycling (Liu et al., 2015). It is also reported that CA practices improve nutrient availability and soil fertility (Choudhary, Datta, et al., 2018; Choudhary, Jat, et al., 2018; Dang et al., 2015). Consequently, increased levels of nitrogen (N), phosphorus (P), and potassium (K) were found in the surface layer under CA compared to CT treatment (Martínez et al., 2016). Recently, CA is gaining momentum because of saving in labour, water, and energy with higher systems' productivity and profitability (Jat, Choudhary, Nandal, et al., 2020; Jat, Datta, Choudhary, Sharma, et al., 2019; Jat, Datta, Choudhary, Yadav, et al., 2019). CA also showed promise in improving soil quality and savings of fertilizer nutrients in reclaimed alkali soils (Choudhary, Datta, et al., 2018; Choudhary, Jat, et al., 2018; Jat et al., 2018; Jat, Datta, Choudhary, Sharma, et al., 2019; Jat, Datta, Choudhary, Yadav, et al., 2019).

Reclamation of sodic soils is mostly done by chemical amendments such as gypsum which supplies Ca^{2+} thereby replacing Na^{+} from clay exchange complex leading to lower soil pH and ESP. In arid and semiarid regions, sodic soils mostly contain an ample amount of native $CaCO_3$ which serves as a potential Ca^{2+} source but its lower solubility makes it difficult for reclamation of sodic soils. Soil pH, partial pressure of CO_2, and its hydrolysis reaction in soil solution control the $CaCO_3$ dissolution rate in soil (Plummer et al., 1978). Several researchers have shown that growing trees or crops has the potential in reclaiming calcareous sodic soils with or without chemical amendments application (Chorom & Rengasamy, 1997; Dagar et al., 2001, 2014, 2016; Dagar & Minhas, 2016; Dagar & Tomar, 2002; Garg, 2000; Mishra et al., 2004; Qadir et al., 2006; Qadir & Oster, 2002; Singh, 2009). In sodic soils, the application of organic material significantly increased the partial pressure of CO_2 into the root zone which leads to the production of carbonic acid and helped in the dissolution of native $CaCO_3$, and supplied Ca^{2+} to soil solution (Amini et al., 2016; Fahu & Keren, 2009; Noori et al., 2021; Tan, 1994). In an extensive review, Leogrande and Vitti (2018) emphasized the important role of organic matter in improving the quality of salt-affected soils by supplying cations and improving soil structure. Organic substances upon decomposition produce organic acids (Trivedi et al., 2017) thereby helping in calcite dissolution and reducing soil pH by supplying Ca^{2+} to soil solution (Filho et al., 2020; Prapagar et al., 2012).

There is hardly any study on how CA mediates soil sodicity through zero tillage (ZT) (or no-tillage) and crop residue recycling. There is speculation that higher crop residues have the potential to reduce the soil pH in long term. Upon decomposition, crop residues produce organic acids and subsequently H^{+} ions and thereby reducing soil pH. Another possible hypothesis is through the dissolution of $CaCO_3$ mediated by organic acids that are produced during crop residue decomposition (Figure 1). Therefore, we hypothesize that long-term CA-based management practices with diverse crop rotation significantly reduce soil pH through higher organic matter build-up in the soil. The objectives were: (i) to study the soil salinity and sodicity parameters under CA practices; and (ii) to evaluate different SOC pools under long-term CA management.

2 | MATERIALS AND METHODS

2.1 | Site description

A field experiment was started in the year 2009–2010 at ICAR-CSSRI (Indian Council of Agricultural Research-Central Soil Salinity Research Institute) Karnal, India (29°42″20.7′ N latitude, 76°57″19.79′ E longitude) at an elevation of 243 m above msl (Figure 2). The region has a semiarid and subtropical climate, with a hot and dry spell from April to June to wet summer spell in July to September, and a cool and dry winter spell from October to March. The mean maximum temperature was 31.68°C during the month of June, whereas the minimum temperature was 11.62°C in the coldest month of January. The average rainfall of the area is 670 mm, 75%–80% of which occurred during the monsoon season. The soil was highly sodic during the 1970s with high pH (pH 10.3 in 1:2.5) and exchangeable sodium percentage (97% at 0–5 cm depth) (Bhumbla et al., 1973). After the establishment of ICAR-CSSRI, the soils were reclaimed through gypsum application, and later on cultivation of crops started (Datta et al., 2015). The soil of the experimental field was silty loam in texture (sand 34%, silt 46%, and clay 20%), low in Walkley and Black organic carbon (0.45%) with alkaline pH (ranging from 7.5 to 9.5).

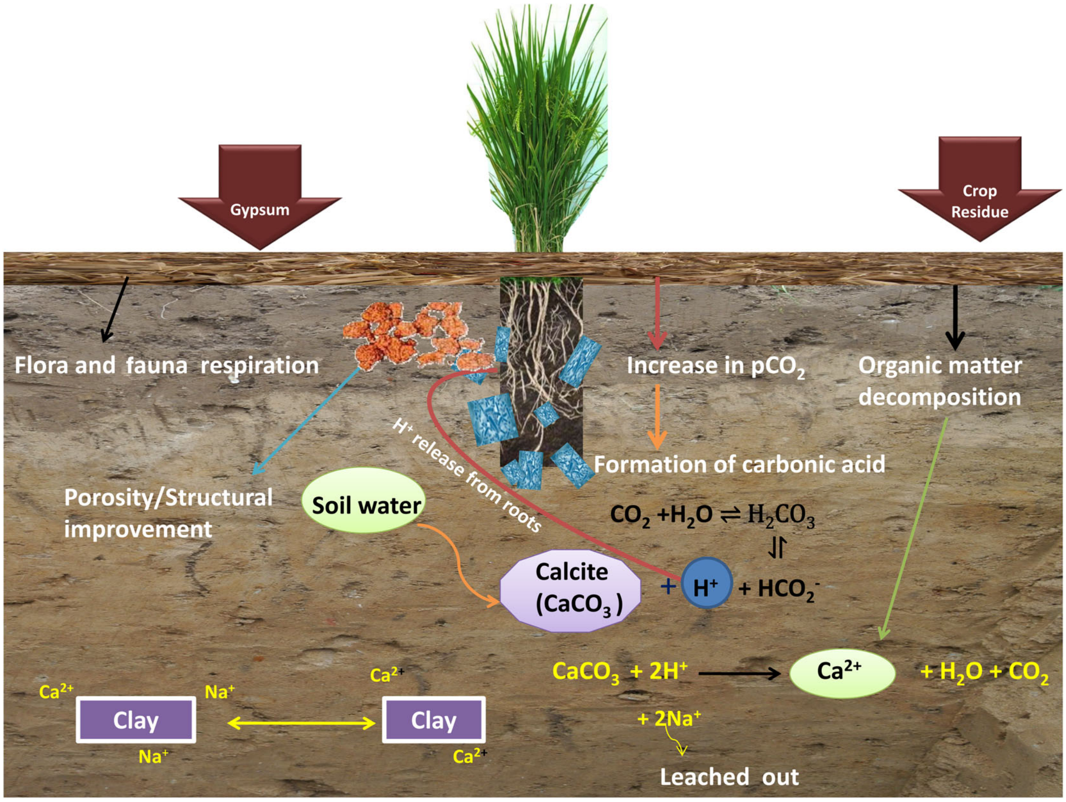

FIGURE 1 Hypothesis of crop residue action in the soil [Colour figure can be viewed at wileyonlinelibrary.com]

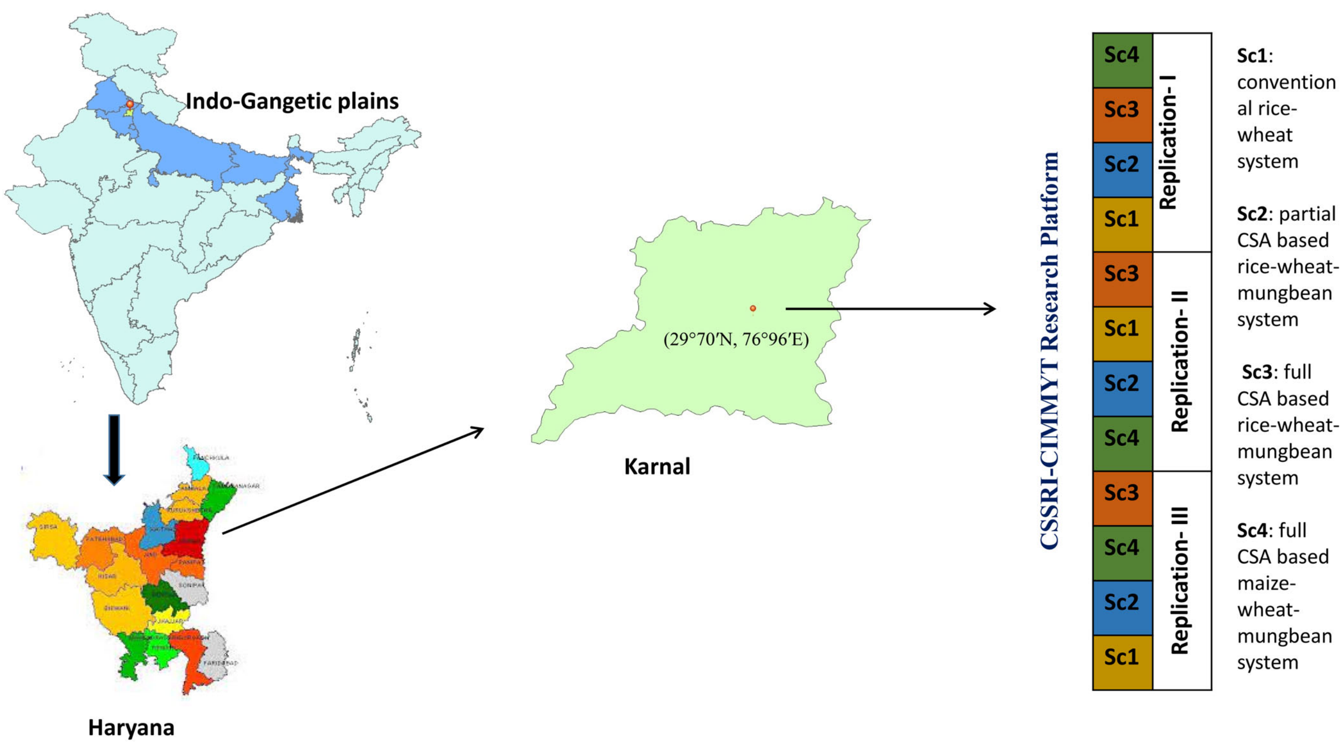

FIGURE 2 Geographic location map of the study area [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Experimental details

In this study, the treatments are termed scenarios (Sc), which were designed to address various drivers of current as well as a future agricultural production system in the western Indo-Gangetic Plains (IGP) of India. Four scenarios with a diversified cereal-based cropping system, tillage and crop establishment, residue management, and water and nutrient management were evaluated. The experiment was laid out in a randomized block design (RBD) with three replications in production-scale plots (2000 m^2; 20 m × 100 m). The scenarios included: Sc1—conventional tilled transplanted rice-conventional tilled wheat (CT-RW) called farmer's practices; Sc2—conventional-tilled-transplanted rice—zero-till wheat-mungbean (CTR-ZTWMb); Sc3—zero-tilled rice-wheat-mungbean (ZT-RWMb) and Sc4—zero-tilled maize-wheat-mungbean (ZT-MWMb). The details of the treatments along with management practices were given in Table S1. The best crop management practices for nutrient, weed, and pest was followed in all scenarios except Sc1, where farmers' practices were followed.

2.3 | Crop managements (crop establishment method, planting, fertilization, etc.)

In Sc1, rice was grown by performing two harrowing plus two cultivator operations followed by wooden planking in dry tillage, whereas puddling was done by passing two harrowing followed by one-time planking. Rice seedlings (20–25 days old) were transplanted manually in the main field after puddling. In CT-wheat, the field was prepared by passing two harrowings and two cultivator operations. Wheat seeds were manually broadcasted in the soil followed by harrowing and planking. In Sc2, rice was transplanted in the main field after puddling and the field preparatory dry tillage was performed by three harrowing and one planking operation. The ZT rice (direct-seeded rice; DSR), wheat, mungbean, and maize were planted by 'Happy Seeder' machine in all CA-based scenarios (Sc2, Sc3, and Sc4). The distance between rows was maintained at 22.5 cm for ZT-rice, wheat, and mungbean, whereas for maize row to row distance was maintained at 67.5 cm. Both rice and maize were sown during June before the onset of the monsoon season, wheat was sown between the last week of October and to the first week of November, and mungbean was cultivated between April to mid-June (between wheat harvesting and rice sowing) every year. The best management practices were followed with the standard seed rates in all crops.

Recommended doses of fertilizers (150–60–60 kg ha^{-1} of N-P_2O_5-K_2O for both rice and wheat) were applied in all CA-based scenarios (Sc2–Sc4). In Sc1, farmers' practices were followed with higher N (175 kg N ha^{-1}), medium P (46 kg ha^{-1}), and no K fertilizer in the plot. The nutrient N was supplied mainly through urea (46% N), however, P and K were supplied through di-ammonium phosphate (DAP) (18:46:00) and muriate of potash (MoP, 60% K_2O), respectively. NPK complex fertilizer (12:32:16) was also used in different scenarios as per recommended dose. In all the scenarios, P and K along with ~17% N were applied as basal, and the remaining N was supplied by urea as a top dressing in three equal splits. In mungbean, no fertilizer was given in Sc2–Sc4.

2.4 | Residue management

In Sc1, 100% rice and wheat residues were removed from the field. In Sc2, 100% rice and 30% wheat residues (anchored wheat stubbles of 20–25 cm height) were kept and 100% mungbean residues were incorporated during the puddling operation in rice. In Sc3, 100% rice and mungbean and 30% wheat residues were kept on the surface. But in Sc4, 65% (anchored stubbles up to cob position) maize, 30% wheat, and 100% mungbean residues were kept on the soil surface. During the experimental period, about 159 Mg ha^{-1} crop residues (including maize, wheat, and mungbean) were recycled in Sc4 whereas in Sc2 and Sc3 about 153 and 139 t ha^{-1} crop residues (including rice, wheat, and mungbean), respectively were recycled (Table S2). For rice and wheat residue, carbon (C) input was calculated assuming a concentration of 0.45 kg C per kg dry matter (Johnson et al., 2006) and for maize residue, 0.40 kg C per kg dry matter (Sawyer & Mallarino, 2007) and for mungbean residue, 0.44 kg C per kg dry matter (Zang et al., 2015). During the experimental period, in Sc2, 41.9, 10.9, and 15.5 t C ha^{-1} were added through rice, wheat, and mungbean crop residues, respectively. Whereas in Sc3 and Sc4, it was 37.1, 10.2, 14.8, and 40.5, 10.7, and 14.8 t C ha^{-1} through rice/maize, wheat, and mungbean, respectively were recycled.

2.5 | Soil sample collection and analysis

In the year 2009–2010, rice was grown as uniformity crop for maintaining the residues. Soil samples were collected after harvesting of common crop wheat in all the scenarios during years 2010 (initial level), 2014 (after 4 years), and 2019 (after 9 years) from 0 to 15 and 15 to 30 cm soil depths using auger with 5 cm internal diameter. The said experiment was started on the partially reclaimed sodic soils where sodic patches have prevailed with varied pH ranging from 7.5 to 9.5. During the wheat season 2009–2010, the sodic spots were identified by observing the patchy growth of the wheat crop (peculiar symptoms of sodic condition) and confirmed by measuring the pH and ESP in each plot. A sizable area (size: ~25 m^2) was earmarked in each plot based on the soil pH. Within each plot, sub-samples were collected from three locations for each pH range, and then a composite sample was prepared for each depth. Part of the soil samples was air-dried in shade, ground to pass through a 2-mm sieve, and stored in plastic containers for analysis of selected soil chemical properties.

Soil pH_2 (soil:water 1:2 ratio) and pHs in the aqueous paste of the soil and water were determined using a digital pH meter (USSL, 1954). Electrical conductivity of soil suspension (soil:water 1:2 ratio) (EC_2) and saturation extract of soil paste (ECe) were measured using an EC meter (USSL, 1954). Sodium and potassium concentrations were determined in soil saturation extract by a flame photometer (Bhargava, 2003; USSL, 1954). Calcium and magnesium concentration were estimated by EDTA method (Schwarzenbach et al., 1946). Carbonate and bicarbonate were determined by titrating the sample against standard acid. Chloride was determined by titrating the soil extract against silver nitrate solution using potassium chromate as an indicator (USSL, 1954) and sulfate was estimated by the turbidimetric method (Chesnin & Yien, 1951). Cation exchange capacity (CEC) and ESP of soils were determined by the method of Tucker (1985). The sodium adsorption ratio (SARe) of soil saturation extract was calculated by the following equation

$$SAR = \frac{[Na^+]}{\sqrt{\frac{([Ca^{2+}]+[Mg^{2+}])}{2}}}$$

Where: $[Na^+]$ represents the concentration of cation in cmol $(p+)L^{-1}$ note halving the sum of $[Ca^{2+}]$ and $[Mg^{2+}]$ before taking the square root.

The oxidizable organic carbon (OC) was determined following the wet oxidation method of Walkley and Black (1934). Very labile carbon (VLC) was measured following Datta, Mandal, et al. (2017) using 12 N H_2SO_4. Total carbon (TC) was measured using the Elementer CN analyzer (Elementer Vario EL Cube). The $CaCO_3$ content of the soils was measured following Collins Calcimeter (Allison & Moodie, 1965). Inorganic carbon (IC) was calculated from $CaCO_3$ content by multiplying 0.12 on a mass basis. Total organic carbon (TOC) was calculated by subtracting IC from TC.

2.6 | Statistical analysis

Data analysis was done with the help of SAS 9.1 software (SAS Institute, 2001). The treatment means were compared by the least significant difference (LSD) test at $p = 0.05$ (Gomez & Gomez, 1984). A Pearson's correlation matrix was constructed among the soil properties studied to determine the common relationships between parameters.

3 | RESULTS

3.1 | Changes in soil pH and EC

Conservation agriculture-based scenarios showed a significant decline in soil pH_2 (soil:water; 1:2) with the increasing years of management at 0–15 cm soil depth (Table 1). A lowest decline in pH_2 (6.98) was observed in Sc2 at 0–15 cm soil depth among the scenarios. At 0–15 cm soil depth, about 8% decline in soil pH_2 after 4-years (year 2014) and 18% decline after 9 years (year 2019) was observed in Sc2 over 2010 level (8.53, initial level). In Sc3, about 8% and 14% decline in soil pH_2 was observed after 4 and 9 years, respectively, compared to the initial level (year 2010) whereas, in Sc4, the decline in soil pH_2 was 4.5% and 12%. At 15–30 cm soil depth, the highest decline in soil pH_2 was observed in Sc2 (15.5%) closely followed by Sc4 (14%) after 9 years (year 2019) over the initial level. A similar observation was also observed in pHs under different scenarios. The lowest pHs were observed in Sc2 (6.37), whereas conventional management did not exert any significant effect on soil pH reduction (Table 1).

Significant variation in EC (EC_2 and ECe) was observed across the years although the values are much lower than the critical level of 4.0 dS m^{-1} above which significant impact on plant growth manifested (Table 2). With progress in cultivation practices, EC_2 decreased (about 28%) significantly after 9-years, the lowest being associated with Sc2 (0.34 dS m^{-1}) and Sc3 (0.33 dS m^{-1}) at 0–15 cm soil depth. However, ~33% decline in EC_2 was observed in Sc3 at 15–30 cm soil depth. A similar observation was also observed in ECe across the years. In the first 4 years, the decline rate of EC was slower (25% of total reduction) and after that the rate was increased exponentially in the last 5 years (75% of total). At 15–30 cm soil depth, about a 29% decline in ECe was observed in CA-based management after 9 years over 4 years (Table 2).

3.2 | Cations and anions

Significant variation in cations was observed among the scenarios except for K^+ ion. With progress in CA-based management,

TABLE 1 Changes in soil pH_2 and pHs under different management scenarios

	pH_2						pHs					
Year	2010		2014		2019		2010		2014		2019	
Soil depth	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Scenario												
Sc1	8.59^{Aa}	8.62^{Aa}	8.46^{Aa}	8.52^{Aa}	8.33^{Aa}	8.58^{Aa}	8.23^{Aa}	8.22^{Aa}	8.02^{Aa}	8.37^{Aa}	8.17^{Aa}	8.35^{Aa}
Sc2	8.53^{Aa}	8.68^{Aa}	7.84^{BCb}	8.16^{ABb}	6.98^{Cc}	7.33^{Cc}	8.13^{Aa}	8.08^{Aa}	7.59^{Bb}	7.99^{ABa}	6.37^{Cc}	7.20^{Bb}
Sc3	8.38^{Aa}	8.56^{Aa}	7.74^{Cb}	8.09^{Bb}	7.24^{BCc}	7.62^{Bc}	8.07^{Aa}	8.18^{Aa}	7.62^{Bb}	7.82^{Bab}	6.99^{Bc}	7.38^{Bb}
Sc4	8.50^{Aa}	8.41^{Aa}	8.12^{Ba}	7.86^{Bb}	7.47^{Bb}	7.25^{Cc}	8.28^{Aa}	8.08^{Aa}	7.59^{Bb}	7.64^{Bb}	7.08^{Bc}	7.21^{Bc}

Note: same upper- and lower-case letters are not significantly different at $p < 0.05$ among the scenarios in a column and the years in rows, respectively, according to the LSD test for separation of the mean. Values are the average of three replicates ($n = 3$).
Abbreviation: LSD, least significant difference.

TABLE 2 Changes in soil EC_2 and ECe (dS m^{-1}) under different management scenarios

Year	EC2						ECe					
	2010		2014		2019		2010		2014		2019	
Soil depth	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Scenario												
Sc1	0.48^Aa	0.51^Aa	0.42^Aa	0.52^Aa	0.38^Aa	0.37^Aa	1.48^Aa	1.25^Aa	1.26^Aa	1.04^Aa	1.29^Aa	1.0^Aa
Sc2	0.45^Aa	0.43^Aa	0.48^Aa	0.43^Aa	0.34^Aa	0.30^Aa	1.38^Aa	1.04^Aab	1.23^Aa	1.28^Aa	1.05^Aa	0.83^Ab
Sc3	0.48^Aa	0.42^Aa	0.45^Aa	0.38^Aa	0.33^Aa	0.28^Aa	1.40^Aa	1.18^Aa	1.34^Aa	1.12^Aa	1.05^Aa	0.78^Ab
Sc4	0.50^Aa	0.44^Aa	0.43^Aab	0.41^Aa	0.36^Ab	0.33^Aa	1.49^Aa	1.10^Aa	1.36^Aa	1.12^Aa	1.04^Ab	0.89^Aa

Note: same upper- and lower-case letters are not significantly different at $p < 0.05$ among the scenarios in a column and the years in rows, respectively, according to the LSD test for separation of the mean. Values are the average of three replicates ($n = 3$).

extractable Na^+ ion concentration decreased significantly over the years (Table 3). After 9 years, the highest decrease in extractable Na^+ ion concentration was observed in Sc4 (49.3%) followed by Sc3 (46%) and Sc2 (45%) at 0–15 cm soil depth over the initial values. Similarly, at 15–30-cm soil depth, a significant decline in extractable Na^+ was recorded in Sc3 (49%) and Sc2 (47%). Extractable Ca^{2+} concentration decreased across the years with the progress of cultivation practices except for Sc3. The highest decrease was observed in Sc1 (19%) followed by Sc2 (8.1%) and Sc4 (5.4%), whereas Sc3 showed a reverse trend with 24% higher after 9 years over the initial level at 0–15-cm soil depth. A similar trend was also observed at 15–30 cm depth except for Sc1 where Ca^{2+} ion concentration increased with years. Extractable Mg^{2+} ion concentration showed significant variation among the scenarios across the years. With progress in cultivation practices, extractable Mg^{2+} ion concentration decreased significantly except for Sc1, the highest and lowest values were associated with Sc3 (20.2%) and Sc2 (3.3%) at 0–15-cm soil depth after 9 years. In Sc1, about 54% higher extractable Mg^{2+} ion concentration was observed after 9 years at surface soil depth. At 15–30-cm soil depth, Sc3 and Sc4 registered a significant decrease in Mg^{2+} ion concentration whereas Sc1 showed a significant increase (54%) after 9 years over the initial level (Table 3).

Extractable anions varied significantly among the scenarios across the years. Except Sc1, extractable carbonate content decreased significantly with progress in CA-based management (Table 4). Sc3 showed a 100% decline in CO_3^{2-} content followed by Sc2 (88%) and Sc4 (81%) at 0–15-cm soil depth after 9-years, whereas about a 98% increase in Sc1 (1.33 me L^{-1}) was observed. At subsurface depth, extractable CO_3^{2-} disappeared in all the scenarios with progress in cultivation. Extractable bicarbonate content exhibited a significant decline after 9 years of CA-based management. After 9 years, the highest and lowest decline was observed under Sc2 (74%) and Sc4 (66%), respectively, at 0–15-cm soil depth over the initial level (11.75 and 13.75 me L^{-1}, respectively). Similar observations were also reported at 15–30 cm soil depth on average with a 50%–59% decline in bicarbonate content. CA-based management resulted in significant decrease in extractable Cl^- content after 9 years of continuous cultivation. The highest decrease in Cl^- content was observed in Sc2 and Sc4 (~39%) followed by Sc3 (22.5%) whereas the conventional system (Sc1) also recorded 19% less Cl^- after 9 years over the initial (Sc1: 5.54 me L^{-1}, Sc2: 4.81 me L^{-1}, Sc4: 9.24 me L^{-1}) at 0–15 cm soil depth. Significantly lower Cl^- was observed in Sc2 (49%) followed by Sc4 (28%), whereas Sc3 (4%) showed the lowest decline in Cl^- at 15–30-cm soil depth after 9 years compared to the initial level. On average, partial CA (Sc2) and CT-based managements (Sc1) facilitated the highest decrease (80%) in extractable SO_4^{2-} concentration at 0–15-cm soil depth after 9 years of cultivation. After 9 years, CA-based managements (Sc3 and Sc4) on average resulted in 63% and 54% decline in SO_4^{2-} concentration at 0–15 and 15–30 cm soil depth, respectively (Table 4).

3.3 | CEC, ESP, and SAR

Long-term CA-based practices resulted in significant increase in CEC of soil across the years compared to CT-based agriculture (Figure 3). At 0–15-cm soil depth, Sc2 and Sc3 recorded 35% and 38% higher CEC after 4 years and about 89% and 58% higher CEC after 9 years over initial level (CEC of 9.06% and 7.73%). Whereas, after 9 years, Sc4 showed 24% higher CEC at 0–15 cm soil depth. At 15–30 cm soil depth, about 21.3% and 21.6%, and 48% and 50% higher CEC was observed in Sc2 and Sc3, respectively, after 4 and 9 years. Sc4 recorded 19% and 30% higher CEC after 4 and 9 years, respectively (Figure 3).

With progress in CA-based managements, ESP decreased significantly over the years (Figure 3). The highest and lowest decrease in ESP was 43% and 4% in Sc2 and Sc3 after 4 years and goes up to 50% and 18% after 9 years compared to the initial level, respectively. At 15–30-cm soil depth, Sc2 recorded the highest decline in ESP after 4 years (49%) and 9 years (60%). Scenario 3 and Sc4 registered 24% and 29% after 4 years and a 37% and 32% decrease in ESP after 9 years, respectively (Figure 3). Across the years of cultivation, both CT and CA practices resulted in significant decline in SAR at both the soil depths. The decline in SAR was in the order of Sc1 > Sc2 > Sc3 > Sc4 at 0–15-cm soil depth, whereas at 15–30-cm soil depth, the order was Sc1 (55%) > Sc3 (52%) > Sc2 (47%) > Sc1 (17%) after 9 years (Table 5).

TABLE 3 Changes in extractable cations (me L^{-1}) under different management scenarios

	Na^+						K^+						Ca^{2+}						Mg^{2+}					
Year	**2010**		**2014**		**2019**		**2010**		**2014**		**2019**		**2010**		**2014**		**2019**		**2010**		**2014**		**2019**	
Soil depth	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**
Scenario																								
Sc1	2.68^{Aa}	2.86^{Aa}	2.57^{Aa}	2.14^{Ab}	1.49^{Ab}	1.7^{Ac}	0.14^{Aa}	0.17^{Aa}	0.1^{Aa}	0.14^{Aa}	0.17^{Aa}	0.11^{Aa}	2.63^{BCa}	1.42^{Ba}	2.00^{Ba}	2.04^{Ba}	2.13^{Ba}	2.04^{Aa}	5.04^{Ab}	3.71^{Aa}	4.25^{Bb}	6.88^{Aa}	7.75^{Aa}	4.25^{Aa}
Sc2	2.46^{Aa}	2.43^{Aa}	2.26^{Aa}	2.23^{Aa}	1.35^{Ab}	1.28^{Ab}	0.14^{Aa}	0.11^{Ba}	0.15^{Aa}	0.07^{Ba}	0.13^{A}	0.09^{Aa}	3.58^{ABa}	2.21^{Aa}	3.42^{Aa}	2.25^{Ba}	3.29^{Aa}	1.75^{Aa}	3.58^{Aa}	3.17^{Aa}	3.42^{Ba}	3.83^{Ba}	3.46^{Ba}	3.29^{Aa}
Sc3	2.63^{Aa}	2.43^{Aa}	2.3^{Aa}	2.13^{Aa}	1.42^{Ab}	1.23^{Ab}	0.16^{Aa}	0.10^{Ba}	0.18^{Aa}	0.09^{Ba}	0.12^{Aa}	0.11^{Aa}	2.50^{Ca}	2.00^{Ab}	3.55^{Aa}	3.85^{Aa}	3.10^{ABa}	1.9^{Ab}	4.7^{Aa}	3.4^{Aa}	4.05^{Ba}	2.40^{Ba}	3.75^{Ba}	2.85^{Aa}
Sc4	2.78^{Aa}	2.45^{Aa}	2.65^{Aa}	2.15^{Aa}	1.41^{Ab}	1.73^{Ab}	0.15^{Aa}	0.10^{Ba}	0.15^{Aa}	0.09^{Ba}	0.13^{Aa}	0.09^{Aa}	4.06^{Aa}	2.38^{Aa}	3.53^{Aa}	1.91^{Bb}	3.84^{Aa}	2.28^{Aa}	4.66^{Aa}	3.03^{Aa}	5.81^{Aa}	3.09^{Ba}	4.28^{Ba}	2.59^{Aa}

Note: same upper- and lower-case letters are not significantly different at $p < 0.05$ among the scenarios in a column and the years in rows, respectively, according to the LSD test for separation of the mean. Values are the average of three replicates ($n = 3$).

TABLE 4 Changes in extractable anions (me L^{-1}) under different management scenarios

	CO_3^{2-}						HCO_3^-						Cl^-						SO_4^{2-}					
Year	**2010**		**2014**		**2019**		**2010**		**2014**		**2019**		**2010**		**2014**		**2019**		**2010**		**2014**		**2019**	
Soil depth	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**	**0–15**	**15–30**
Scenario																								
Sc1	0.67^{Ba}	2.17^{Aa}	0.50^{Aa}	0.0^{Ab}	1.33^{Aa}	0.0^{Ab}	13.79^{Aa}	6.68^{Aa}	12.46^{Aa}	6.46^{Ba}	3.75^{Ab}	3.04^{Aa}	5.54^{Ba}	7.37^{Aa}	6.01^{Ba}	5.74^{Aa}	4.48^{Aa}	6.43^{Aa}	8.1^{Aa}	5.19^{Aa}	2.07$^{C b}$	1.69^{Bb}	1.59^{Ab}	1.79^{Ab}
Sc2	2.75^{Aa}	0.25^{Aa}	0.67^{Aa}	0.75^{Aa}	0.33^{Aa}	0.0^{Aa}	11.75^{Aa}	9.63^{Aa}	10.54^{Aa}	9.29^{ABa}	3.04^{Ab}	3.96^{Ab}	4.81^{Ba}	6.92^{Aa}	5.11^{Ba}	5.88^{Aa}	2.94^{Aa}	3.55^{Ab}	7.66^{Aa}	6.16^{Aa}	7.87^{ABa}	4.38^{Aa}	1.55^{Ab}	1.88^{Ab}
Sc3	0.40^{Ba}	1.29^{Aa}	0.0^{Aa}	0.13^{Aa}	0.0^{Aa}	0.0^{Aa}	10.4^{Aa}	6.85^{Ab}	13.5^{Aa}	12.51^{Aa}	2.9^{Ab}	3.12^{Ab}	5.06^{Bb}	5.12^{Ab}	9.97^{Aa}	7.45^{Aa}	3.92^{Ab}	4.9^{Ab}	7.51^{Aa}	4.49^{Aa}	8.75^{Aa}	4.38^{Aa}	2.62^{Aa}	1.85^{Aa}
Sc4	1.00^{Ba}	1.17^{Aa}	1.06^{Aa}	0.50^{Aa}	0.19^{Aa}	0.0^{Aa}	13.75^{Aa}	7.5^{Ab}	11.63^{Aa}	13.00^{Aa}	4.63^{Ab}	3.79^{Ab}	9.24^{Aa}	5.7^{Aa}	6.04^{Bb}	6.64^{Aa}	5.6^{Ab}	4.08^{Aa}	8.66^{Aa}	5.27^{Aa}	5.66^{Bb}	3.37^{ABa}	3.43^{Ab}	2.59^{Aa}

Note: same upper- and lowercase letters are not significantly different at $p < 0.05$ among the scenarios in a column and the years in rows, respectively, according to the LSD test for separation of the mean. Values are the average of three replicates ($n = 3$).

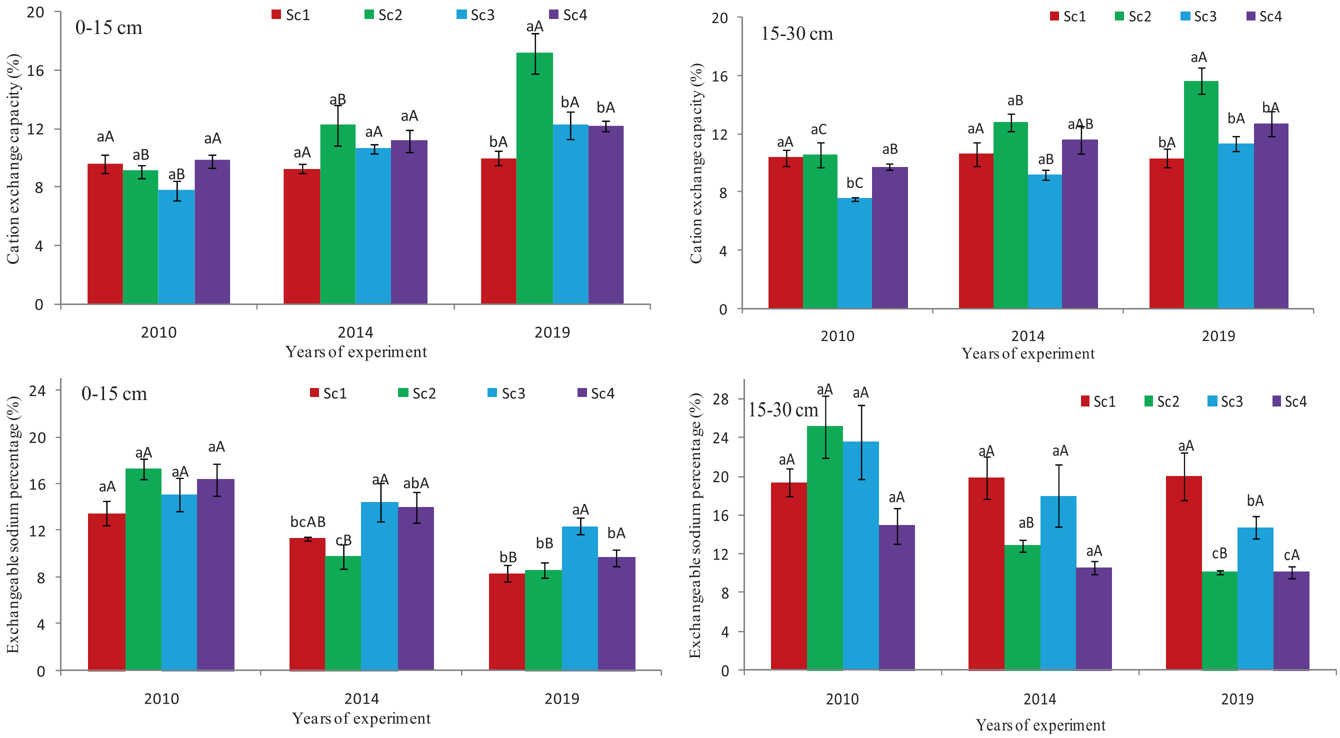

FIGURE 3 Variation in cation exchange capacity and exchangeable sodium percentage of soil under different management scenarios. Sc1: conventional rice-wheat system, Sc2: conventional rice-zero tillage wheat and mungbean system, Sc3: CA-based rice-wheat-mungbean system, Sc4: CA-based maize-wheat-mungbean system. The error bar represents the standard error of the mean. Similar lower-case letters above error bars are not statistically significant at a 5% level of significance between different scenarios. Similar upper-case letters are not statistically significant at a 5% level of significance among the years of experiment. CA, conservation agriculture. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Changes in sodium adsorption ratio (SAR) under different management scenarios

Year	2010	2014	2019	2010	2014	2019
Soil depth	0–15	0–15	0–15	15–30	15–30	15–30
Scenario						
Sc1	1.28^{Ab}	1.50^{Aa}	0.73^{Bc}	2.13^{Aa}	1.19^{Db}	0.95^{Bc}
Sc2	1.20^{Ab}	1.55^{Aa}	0.76^{Bc}	1.64^{Ba}	1.52^{Ca}	0.87^{Bb}
Sc3	1.12^{Ba}	1.23^{Ba}	0.77^{Bb}	1.67^{Ba}	1.81^{Ba}	0.81^{Bb}
Sc4	1.17^{ABa}	1.18^{Ba}	1.04^{Ab}	1.70^{Bb}	2.23^{Aa}	1.41^{Ac}

Note: same upper- and lower-case letters are not significantly different at $p < 0.05$ among the scenarios in a column and the years in rows, respectively, according to the LSD test for separation of the mean. Values are the average of three replicates ($n = 3$).

3.4 | $CaCO_3$ content

Significant variation in $CaCO_3$ content was observed among the scenarios except Sc4 (Figure 4). After 4 years, a similar magnitude of the decline in $CaCO_3$ content was recorded in Sc1 (53%), Sc2 (50%), and Sc3 (50%) at 0–15-cm soil depth. However, after 9 years, the highest decline was associated with Sc3 (46%). At 15–30-cm soil depth, after 4 years, Sc3 (41%) and Sc1 (38%) recorded a significant decline in $CaCO_3$ content whereas Sc4 showed a 25% increase over initials. However, after 9 years, a significant decline in $CaCO_3$ content was observed in Sc3 (24%) followed by Sc1 (19%) at 15–30-cm soil depth (Figure 4).

3.5 | Inorganic carbon

A significant decline in IC was observed under CA-based management (Figure 4). After 9 years, at 0–15-cm soil depth, Sc2 registered a significant decline (59%) in IC followed by Sc3 (52%) compared to initial values. After 4 years, Sc3 showed a 45% decrease in IC content over

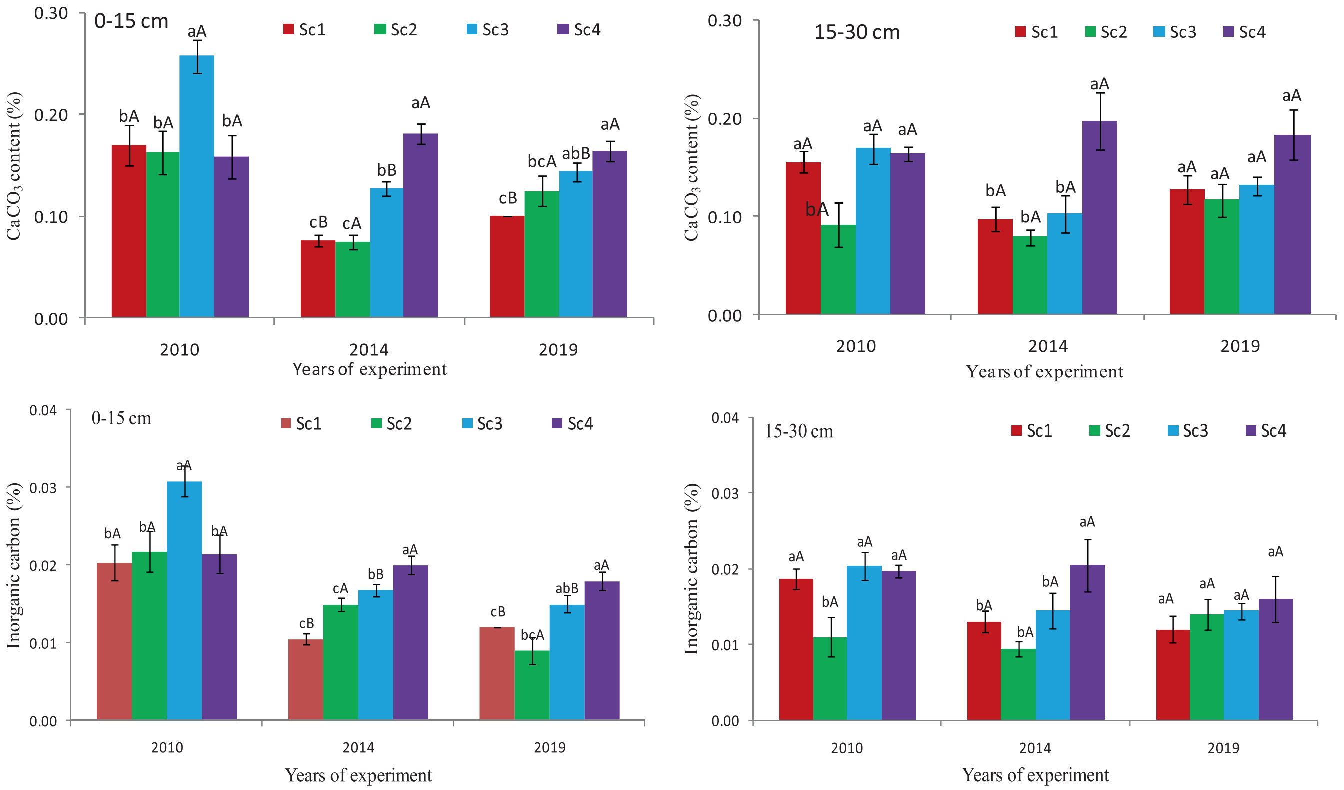

FIGURE 4 Variation in $CaCO_3$ and inorganic carbon content (%) in soil under different management scenarios. Sc1: conventional rice-wheat system, Sc2: conventional rice-zero tillage wheat and mungbean system, Sc3: CA-based rice-wheat-mungbean system, Sc4: CA-based maize-wheat-mungbean system. The error bar represents the standard error of the mean. Similar lower-case letters above error bars are not statistically significant at a 5% level of significance between different scenarios. Similar upper-case letters are not statistically significant at a 5% level of significance among the years of experiment. CA, conservation agriculture. [Colour figure can be viewed at wileyonlinelibrary.com]

the initial level. In both the years, the lowest decline was associated with Sc4 (9% and 18%) in surface soil. At 15–30-cm soil, Sc1 recorded highest decline (30%) followed by Sc3 (29%) and Sc2 (14%) after 4 years. In 2019, IC decreased significantly in Sc1 (36%) followed by Sc3 (29%) and Sc4 (19%), whereas Sc2 recorded 27% higher IC at 15–30-cm soil depth compared to the initial level (Figure 4).

3.6 | OC pools

3.6.1 | Very labile carbon

Year's together practice with CA had resulted in significant increase in VLC across the scenarios (Figure 5). After 9 years, Sc3 recorded, about 175% higher VLC over the initial level at 0–15-cm soil depth. Sc1 (114%), Sc2 (59%), and Sc4 (55%) also showed significant increase in VLC over 9 years of continuous cultivation. After 4 years, increase in VLC was in the order of Sc1 (50%) > Sc4 (41%) > Sc3 (31%) > Sc2 (28%) at 0–15-cm soil depth over the initial level. At 15–30-cm soil depth, Sc4 showed higher VLC by 24% and 57% after 4 and 9 years, respectively. Sc1 also showed 21% and 26% higher VLC at 15–30-cm soil depth after 4 and 9 years. Sc2 and Sc3 showed similar VLC across the scenarios and over the years of cultivation (Figure 5).

3.6.2 | Walkley and Black oxidizable organic carbon

After 4 years, a significant increase in Walkley and Black carbon (WBC) was observed in CA-based scenarios, the highest being associated with Sc3 (62%) followed by Sc4 (60%) and Sc1 (52%) at 0–15-cm soil depth. Whereas, after 9 years, Sc4 (76%) showed thehighest increase in WBC followed by Sc3 (69%) and Sc2 (62%). At 15–30-cm soil depth, about a 14% decline in WBC was observed in Sc1 after 9 years over the initial level of 0.36%. After 9 years, the highest increase in WBC was observed in Sc2 (66%) at 15–30-cm soil depth followed by Sc4 (47%) and Sc3 (38%). In 2014, 14%–38% higher WBC was recorded as compared to 2010 irrespective of scenarios (Figure 5).

3.6.3 | Total organic carbon

Total organic carbon also showed a similar trend as WBC among the scenarios across the years (Figure 6). With progress in cultivation, Sc4 showed higher TOC (77%) followed by Sc3 (69%) and Sc2 (65%) at 0–15-cm soil depth after 9 years of experimentation. After 4 years, TOC was 61% higher in Sc4 and Sc3, and 54% in Sc2 over Sc1. At 15–30-cm soil depth, Sc1 registered a 13% decline in TOC after 9 years, whereas Sc2 recorded the highest TOC (65%) followed by Sc4 (46%)

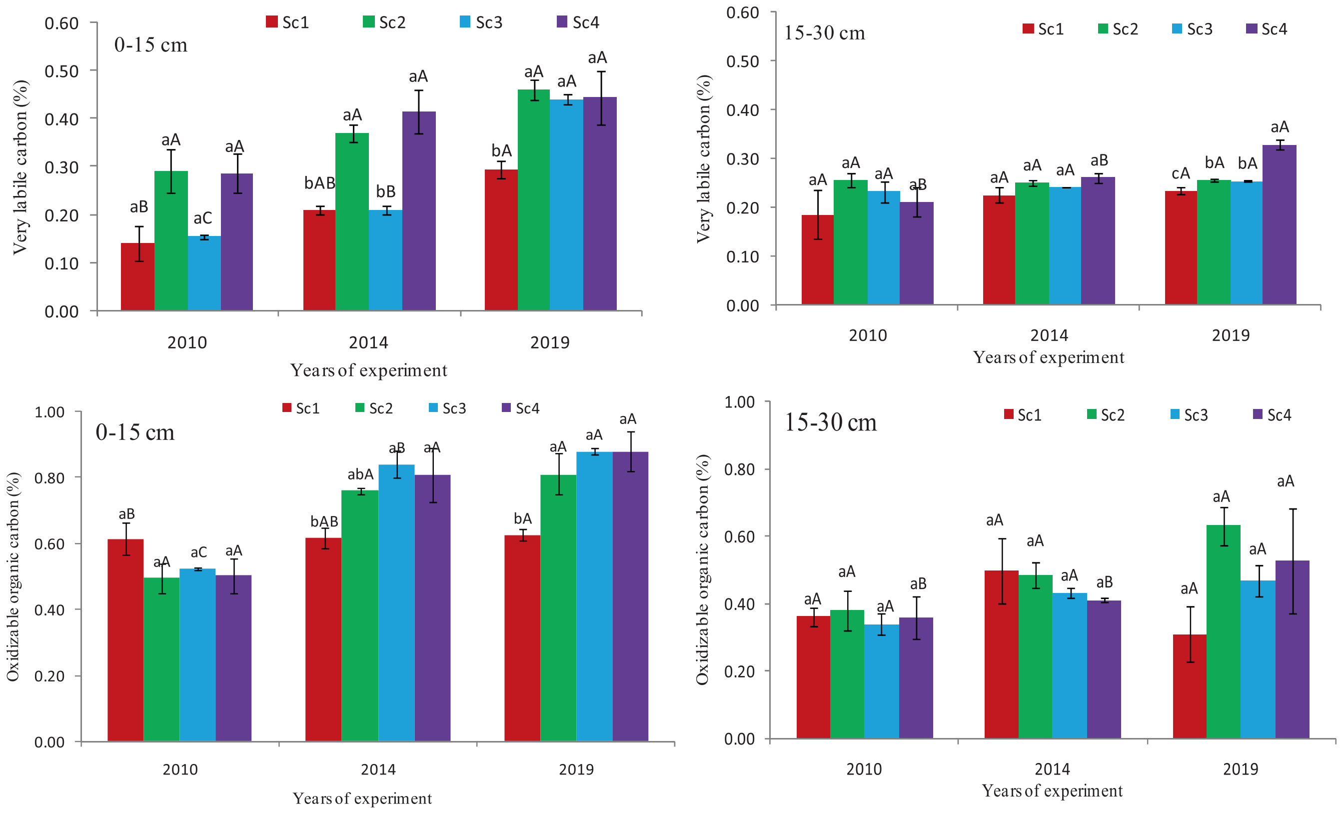

FIGURE 5 Variation in very labile and oxidizable organic carbon content in soil under different management scenarios. Sc1: conventional rice-wheat system, Sc2: conventional rice-zero tillage wheat and mungbean system, Sc3: CA-based rice-wheat-mungbean system, Sc4: CA-based maize-wheat-mungbean system. The error bar represents the standard error of the mean. Similar lower-case letters above error bars are not statistically significant at a 5% level of significance between different scenarios. Similar upper-case letters are not statistically significant at a 5% level of significance among the years of experiment. CA, conservation agriculture. [Colour figure can be viewed at wileyonlinelibrary.com]

and Sc3 (40%). After 4 years, Sc1 showed 39% higher TOC followed by Sc3 (28%), Sc2 (26%), and lowest in Sc4 (13%) over the initial level (Figure 6).

3.6.4 | Total carbon

After 4 years, a similar increase in TC was observed in Sc3 (60%) and Sc4 (61%), whereas Sc2 registered about 51% increase at 0–15-cm soil depth over the initial level (Figure 6). Whereas, after 9 years, Sc4 recorded 74% higher TC followed by Sc3 (63%) and Sc2 (61%) at 0–15-cm soil depth. CT-based practices (Sc1) did not show any increase in TC content over the years. At 15–30-cm soil depth, Sc2 recorded significantly higher TC (64%) after 9 years followed by Sc4 (44%) and Sc3 (35%), whereas Sc1 showed a 15% decline in TC compared to the initial level. Whereas, after 4 years, Sc4 and Sc3, recorded 14% and 24% higher TC compared to Sc1.

3.6.5 | Interaction effects among the soil parameters

Significant interactions were observed among the scenarios, years, and scenarios × years (Table 6). Extractable Ca^{2+} showed a significant effect ($p < 0.001$) of scenarios at 0–15-cm soil depth, whereas the scenarios effect on K^+ and Mg^{2+} was significant ($p < 0.001$) at 15–30 cm soil depth (Table 6). Different carbon pools such as VLC, WBC, IC, TOC, and TC were significantly influenced by scenarios except at 15–30-cm soil depths for WBC, TOC, and TC. $CaCO_3$, ESP, and pH_2 were significantly influenced ($p < 0.001$) by scenarios at both the soil depths. Different CA-based management scenarios significantly influenced EC_2, EC_e, extractable Na^+, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, VLC, WBC, TOC, IC, TC, $CaCO_3$, CEC, ESP, pH_2, and pHs at both the soil depths except IC and $CaCO_3$ at 15–30-cm soil depth and Cl^- at 0–15-cm soil depth. Significant positive interaction was observed for extractable Mg^{2+}, WBC, TOC, and TC at 0–15-cm soil depth (Table 6).

3.6.6 | Relationships among the soil properties

Pearson's correlations matrix has been constructed among the soil properties studied (Table 7). Significant correlations were observed among the soil properties. Soil pH_2 was significantly positively correlated to pHs, EC_2, Na, Cl^-, ESP, and SAR, whereas negatively correlated to Ca^{2+}, CEC, TOC, and VLC. Soil EC_2 was significantly positively correlated to pHs, ECe, Na^+, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, SAR, and negatively correlated to CEC and VLC. ECe was significantly positively

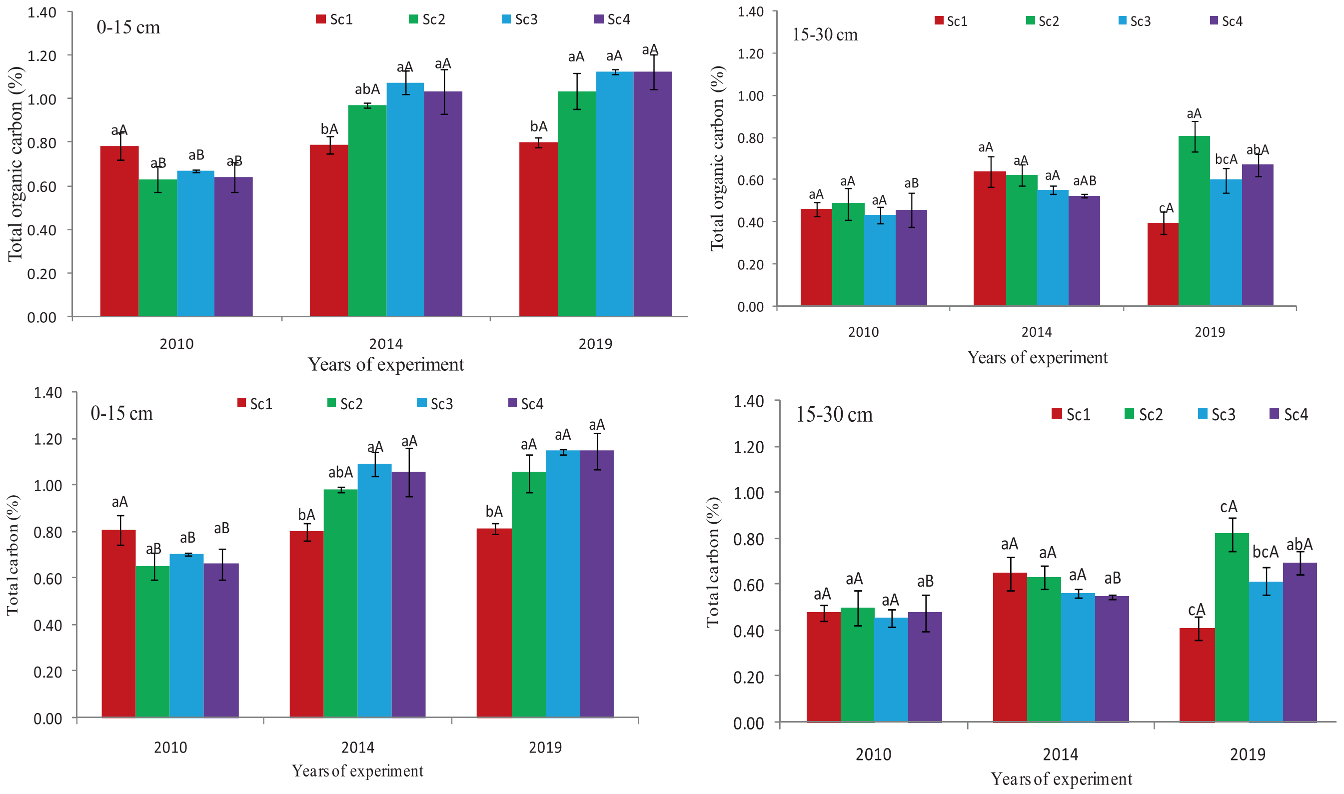

FIGURE 6 Variation in total organic carbon and total carbon content in soil under different management scenarios. Sc1: conventional rice-wheat system, Sc2: conventional rice-zero tillage wheat and mungbean system, Sc3: CA-based rice-wheat-mungbean system, Sc4: CA-based maize-wheat-mungbean system. The error bar represents the standard error of the mean. Similar lower-case letters above error bars are not statistically significant at a 5% level of significance between different scenarios. Similar upper-case letters are not statistically significant at a 5% level of significance among the years of experiment. CA, conservation agriculture. [Colour figure can be viewed at wileyonlinelibrary.com]

correlated to Na^+, Mg^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, and negatively correlated to CEC. Extractable Na^+ was significantly positively correlated to CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, ESP, SAR, and negatively correlated to CEC and VLC. CEC was significantly positively correlated to TOC and VLC, whereas negatively correlated to ESP of soil. TOC was significantly negatively correlated to ESP, SAR, and positively correlated to VLC. ESP was significantly negatively correlated to VLC (Table 7).

4 | DISCUSSION

4.1 | Changes in soil pH and EC under different CA practices

With progress in CA-based management, soil pH (pH_2 and pHs) declined significantly which might be due to the decomposition of crop residues recycled over the years (Filho et al., 2020). During the decomposition of crop residues, partial pressure of CO_2 increased significantly leading to the production of carbonic acids which declined soil pH and subsequently enhanced the dissolution of native $CaCO_3$ (Fahu & Keren, 2009; Prapagar et al., 2012). Similar observations were reported under ZT with crop residue retention compared to CT with crop residue removal (Gura & Mnkeni, 2019; Kibet et al., 2016; Mtyobile et al., 2019). Soil pH was lower under CA-based management systems, supporting previous studies (Gura & Mnkeni, 2019; Jat et al., 2018). The lower pH in CA might be due to the accumulation of soil organic matter (SOM) and soil with crop residue, increasing the number of electrolytes and then decreasing pH (Rahman et al., 2008). The inclusion of legume crop (mungbean) between rice and wheat and incorporation of its residues also facilitated a reduction in soil pH as reported by many researchers (Dhar et al., 2014; Islam et al., 2019). Higher crop residue retention in CA-based managements resulted in the production of organic acids upon decomposition which diluted salt concentration leading to lower EC in soil (Rahman et al., 2008). SOC also improved the soil's physical structure which facilitated the leaching of salts from the upper soil layer. A higher decrease in soil pH and EC was recorded with Sc2 compared to other scenarios where residues were incorporated during puddling (churning of soil in presence of water) of soil for rice transplanting. Incorporation hastens the crop residue decomposition process and secrets more organic acids.

4.2 | Changes in cations and anions, CEC and ESP under different CA practices

Crop residue retention is the main factor in the scenarios to improve CEC in this study. The increase in CEC (Murphy et al., 2016) and Ca^{2+}

TABLE 6 ANOVA of soil properties and interactions effect

Parameters	EC_2		ECe		Na^+		K^+		Ca^{2+}		Mg^{2+}		CO_3^{2-}		HCO_3^-		Cl^-		SO_4^{2-}	
Soil depth	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Scenarios (S)	NS	NS	NS	NS	NS	NS	NS	**	**	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS
Years (Yr)	**	**	**	**	**	**	NS	NS	NS	NS	NS	NS	*	**	**	**	NS	**	**	**
S × Y	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
Parameters	**VLC**		**WBC**		**TOC**		**IC**		**TC**		**$CaCO_3$**		**CEC**		**ESP**		**pH_2**		**pHs**	
Soil depth	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Scenarios (S)	**	**	*	NS	*	NS	**	**	*	NS	**	**	NS	NS	**	**	*	**	*	**
Years (Yr)	**	**	**	*	**	*	**	NS	**	**	**	NS	**	**	**	**	**	**	**	**
S × Y	NS	NS	**	NS	**	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	*

Abbreviations: CEC, cation exchange capacity; ESP, exchangeable sodium percentage; IC, inorganic carbon; TC, total carbon; TOC, total organic carbon; VLC, Very labile carbon; WBC, Walkley and Black carbon.
*Indicates significant at <0.05 level.
**Indicates significant at <0.001.

after the retention of crop residue were previously reported (Mohanty et al., 2015). Although, the increase in the availability of Mg and K was reported by Yang et al. (2017) and, Gura and Mnkeni (2019) under no-tillage (NT) with crop residue retention compared to the CT practices but in our study, this trend was not observed. Many researchers (Godde et al., 2016; Haruna & Nkongolo, 2020) reported that crop residue retention increases the SOM which is the main factor in the increase of CEC and available Mg, K, and Ca. Our study suggests that in marginal soils CEC and Ca^{2+} are also more sensitive toward crop residue retention than Mg^{2+} and K^+. Organic acids produced upon decomposition of crop residues (Filho et al., 2020; Prapagar et al., 2012) and carbonic acids generated from higher partial pressure of CO_2 during microbial and root respiration had resulted in dissolution of native Ca^{2+} from $CaCO_3$ concretions (Fahu & Keren, 2008; Qadir et al., 2005) which replace thee Na^+ from exchange phase and good soil structure facilitated leaching of Na from upper soil layers. As a result, soil ESP also declined under CA-based management over the years. Availability of Na was lower under NT but not at the cost of good crop production than in CT, supporting previous studies (Loke et al., 2014). Good soil structure due to higher SOC content under CA-based management also enhanced the leaching of Cl^- and SO_4^{2-} from upper soil layers under CA-based management (Leogrande & Vitti, 2018) which explains the lower concentration in those scenarios. In CA-based scenarios (Sc2–Sc4), increased content of SOC facilitated the improved soil structure and physical conditions which facilitated in increasing the CEC and reducing the ESP over the years. Both rice-based systems (Sc2 and Sc3) were found better with regard to cations and anions as compared to CT-based rice (Sc1) and CA-based maize system (Sc4).

4.3 | Variation in SOC pools under different CA practices

Higher VLC in CA-based management practices was due to long-term crop residue retention at the soil surface which upon decomposition releases labile carbon into the soil. Jat, Datta, Choudhary, Sharma, et al. (2019) also reported higher labile carbon content in surface soil under CA-based management. Higher microbial activity in surface soil under CA-based management also contributed to higher production of VLC in those scenarios (Choudhary, Datta, et al., 2018; Choudhary, Jat, et al., 2018). Parihar et al. (2018) also reported higher VLC as MBC at surface soils under CA-based management in Northwest India. All CA-based managements resulted in higher SOC in comparison with CT. The increased SOC is likely related to the redistribution of SOC within aggregates, which increases its stability under CA (Sheehy et al., 2015). The greater soil aggregation would slow down the SOM decomposition rates in CA practices (Jat, Datta, Choudhary, Yadav, et al., 2019; Sauvadet et al., 2018). The improvement of SOC stock in the topsoil (0–15 cm) is greater than in the subsoil (15–30 cm) is in line with the positive effects of CA practices on SOC stock being mainly limited to surface soil layers (Badagliacca et al., 2018; Hubbard et al., 2013; Sun et al., 2020). In the subsoil

TABLE 7 Pearsons correlations among the soil properties irrespective of scenarios

Correlations	pH_2	EC_2	pH_s	EC_e	Na^+	Ca^{2+}	Mg^{2+}	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	CEC	TOC	ESP	$CaCO_3$	VLC	SAR
pH_2	1																
EC_2	0.52[a]																
pH_s	0.91[a]	0.52[a]															
EC_e	0.26	0.74[a]	0.20														
Na	0.60[a]	0.86[a]	0.62[a]	0.75[a]													
Ca	−0.46[b]	0.10	−0.33	0.38	0.07												
Mg	0.06	0.36	−0.03	0.41[b]	0.08	−0.01											
CO_3	0.36	0.46[b]	0.22	0.54[a]	0.51[b]	0.02	0.12										
HCO_3	0.30	0.65[a]	0.41[b]	0.73[a]	0.78[a]	0.36	0.01	0.24									
Cl	0.47[b]	0.52[a]	0.58[a]	0.43[b]	0.56[a]	0.25	0.01	0.04	0.63[a]								
SO_4	0.25	0.66[a]	0.30	0.73[a]	0.72[a]	0.48[b]	−0.06	0.37	0.74[a]	0.53[a]							
CEC	−0.74[a]	−0.52[a]	−0.71[a]	−0.50[b]	−0.63[a]	0.02	−0.20	−0.36	−0.46[b]	−0.44[b]	−0.42[b]						
TOC	−0.72[a]	−0.20	−0.69[a]	0.09	−0.32	0.55[a]	0.23	−0.26	−0.05	−0.19	0.03	0.46[b]					
ESP	0.74[a]	0.38	0.67[a]	0.05	0.46[b]	−0.17	−0.09	0.18	0.15	0.41[b]	0.24	−0.56[a]	−0.63[a]				
$CaCO_3$	−0.01	0.11	−0.01	0.22	0.23	0.03	−0.04	0.17	0.10	−0.03	0.28	−0.26	−0.08	0.00			
VLC	−0.77[a]	−0.42[b]	−0.74[a]	−0.24	−0.51[b]	0.51[b]	−0.01	−0.11	−0.38	−0.39	−0.25	0.59[a]	0.66[a]	−0.45[b]	−0.1		
SAR	0.57[a]	0.46[b]	0.64[a]	0.16	0.61[a]	−0.21	−0.39	0.29	0.50[b]	0.43[b]	0.28	−0.32	−0.52[a]	0.32	0.07	−0.39	1

Abbreviations: CEC, cation exchange capacity; ESP, exchangeable sodium percentage; TOC, total organic carbon; VLC, Very labile carbon; SAR, sodium adsorption ratio.

[a]Correlation is significant at the 0.01 level (two-tailed).

[b]Correlation is significant at the 0.05 level (two-tailed).

physical accessibility of the organic C to microorganisms was a major control of carbon (C) dynamics (Salome et al., 2010). Higher microflora and fauna resulted in higher C content in CA-based management systems (Choudhary, Datta, et al., 2018; Choudhary, Jat, et al., 2018). The results of SOC stock in the subsoil are thus probably due to the reduction of soil disturbance in CA systems, affecting the vertical separation of decomposers and the substrate in the subsoil (Li et al., 2018; Mondal et al., 2020). At the field scale, spatial heterogeneity in C content was also greater in the subsoil than in topsoil (Salome et al., 2010). Collectively, as compared to the topsoil, subsoil has less potential in gaining SOC stock with the application of conservation tillage practices (Mondal et al., 2020). The SOC pools under different scenarios depend upon the organic residues recycled over the years. Across the soil depth (0–30 cm), the SOC content is more or less the same under different CA-based scenarios but it varied with management (retention vs. incorporation) in upper and lower layers. With progress in CA-based management $CaCO_3$ and IC content decreased in soil. In addition, higher partial pressure of CO_2 due to higher microbial activity and root respiration during decomposition of crop residues facilitated the production of carbonic acids which mainly attack native $CaCO_3$ (Qadir et al., 2005) and causes its dissolution and release Ca^{2+} ions into soil solution (Fahu & Keren, 2008, 2009). As a result, $CaCO_3$, as well as IC concentration reduced and soil pH and ESP, decreased through natural reclamation of sodic soils. In CA-based management, a higher fungal and bacterial population and higher abundance of copiotrophs resulted in the accelerated crop residue decomposition (Choudhary et al., 2020; Choudhary, Datta, et al., 2018; Choudhary, Jat, et al., 2018; Choudhary, Sharma, et al., 2018). Kim et al. (2020) observed increased $CaCO_3$ dissolution due to increased soil water storage and transport resulting from agricultural management such as crop cultivation. The acids released by the microbes helped to the dissolution of $CaCO_3$ and subsequently lower IC (Pal, 2013).

4.4 | Relationships among the soil properties irrespective of scenarios

Significant relationships were observed among the soil properties irrespective of management scenarios. Higher soil pH resulted due to higher Na^+ concentration, ESP, and SAR thereby explaining positive relations among them whereas higher Ca^{2+} ion reduces the soil pH. The SOC under CA-based systems (Sc2–Sc4) showed a negative correlation with ESP and pH. A negative correlation between SOC and soil pH and ESP might be due to higher soil pH and Na^+ ion concentration which results in the dispersion of soil due to the prevalence of sodium ions thereby favoring oxidation of SOC. The partial CA-based rice system (Sc2) recorded the lowest pH and followed by Sc3 and Sc4 and the highest with Sc1 (CT system). The incorporation of crop residue lowers the pH across the profile in Sc2. Li et al. (2020) also observed a negative correlation between soil pH and SOC stock in a global meta-analysis to evaluate the effect of crop residue retention and minimum tillage on SOC storage. Chandel et al. (2021) also reported that soil pH and SOC were negatively correlated while studying the effect of saline irrigation water on seed spices. Malobane et al. (2020) reported a significant increase in CEC upon 30% crop residue retention in sorghum-based cropping systems in marginal soils of South Africa. Higher TOC in soil releases more VLC due to higher microbial activity in CA-based management. Significant correlations between TOC and VLC were observed by Datta et al. (2015) while studying the distribution of SOC under different land uses in reclaimed sodic soil.

In our study, different scenarios (portfolio of interventions varied in the cropping system, tillage, crop establishment, residue management, and fertilizer management) were compared to find out the best scenario. Earlier, most of the published work is related to comparison between individual treatments like ZT versus CT and with residue and without residue, etc. So, we have evaluated the portfolio of intervention (scenario) in CA-based cereal systems of IGP and suggested that CA-based rice-wheat-mungbean system has the ability to reclaim the sodic soils over a period of time. Thus, farmers of IGP are advocated to adopt the CA-based management practices in both normal as well as salt-affected soils in their existing rice-wheat system for soil quality restoration.

5 | CONCLUSIONS

Long-term CA has the potential to reclaim the degraded lands (sodic soils) in intensive cereal-based systems of western IGP. The SOC pools increased significantly due to higher carbon input in the form of crop residues which helped in reducing soil pH. Results showed that partial CA-based rice-wheat-mungbean systems (Sc2) found more suitable in reducing the soil pH, EC, and ESP, and in improving the cation exchange capacity of sodic soil as compared to other scenarios. The full CA-based rice-wheat-mungbean system (Sc3) is more effective in the reclamation of sodic soils as compared to the maize-wheat-mungbean system (Sc4). In CA systems, ZT with crop residue recycling helped in improving the SOC by ~65%–75% over initial values after 9 years of continuous cultivation. So, it is evident that CA-based scenarios improved the soil chemical conditions which is required for the good soil health for getting higher yields. Thus, the present findings confirm the benefits of CA in enhancing soil quality in degraded ecosystems. In the rice-wheat system of IGP, about 1.8 million ha area is affected by soil sodicity and it can be reclaimed by following the CA-based management practices as plenty of crop residues are available freely and may be used for productive purposes. Therefore, CA is an excellent supplement that can be used for the reclamation of calcareous sodic soils to improve the reclamation efficiency and deserves further investigation in highly sodic soils.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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