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Article

Biological and Chemical Vicissitudes in Soil Rhizosphere Arbitrated Under Different Tillage, Residues Re-Cycling and Oilseed Brassica-Based Cropping Systems

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Abstract: The impact of long-term soil and crop management practices on soil biological and chemical properties in oilseed brassica-based production systems were deliberated for holistic soil health improvement in the present study. Different tillage, crop residue re-cycling and cropping systems were studied for 5-years in 0-15 and 15-30 cm soil profiles. No-till permanent beds with crop residue (PB+R) noticeably improved soil organic carbon (SOC), microbial biomass carbon (MBC), enzymes [dehydrogenase (DHA) and alkaline phosphatase (ALP)], nitrogen fractions (available, nitrate and total), and available phosphorus and potassium content in both the soil layers compared to conventional tillage without crop residues. Though, the plow soil layer (0-15 cm) showed higher concentration of soil carbon, enzymes, N fractions and available P than in the sub soil (15-30 cm). The dynamic soil biological and chemical properties were also varied with the crop stage, and recorded higher MBC at 30 days, SOC and enzymatic activities at 60 days, and N fractions and available P and K at harvest of mustard crop. Green gram-mustard rotation showed higher values of biological and chemical parameters. Thus, the legume-based mustard crop rotation following no-till permanent beds and residue re-cycling found holistic in improving soil health, and nutrient cycling.

Keywords: soil organic carbon; soil enzyme; soil nutrients; tillage; mustard-based cropping systems; crop residue re-cycling

Introduction

Indian food grain production achieved self-sufficiency or even more at present (325 mt in 2023), which is about to reach the target of half of the 21st century (333 mt)¹. However, the shrinking land resource base due to expanding population and severe degradation of soil and water resources led to reduction in inputs use efficiency amid changing climate scenario². In conventional agricultural, intensive use of machinery and chemical inputs caused deterioration in soil quality; increased soil compaction, water erosion and salinization; and decreased soil organic matter (SOM), nutrient content and biodiversity which negatively impacted the soil productivity and sustainability³. The conservation agriculture (CA) practices have clear advantages over the conventional agricultural practices in improving the soil health and the efficient use of natural resources, reducing the environmental impacts of agricultural activities, saving inputs, reducing the cost of production, etc⁴. Extensive research has demonstrated that conservation agriculture improved soil physico-chemical and biological properties that are crucial for maintaining soil health, and increasing agro-ecosystems resilience to global climate change⁵. The CA components comprised no tillage, residue re-cycling and cropping system diversification have multiple benefits to the physico-chemical, and biological properties of soil^{6,7}. It mainly improves the soil organic carbon (SOC) stock and minimize the input use during the cultivation of crops⁸.

Soil organic matter is the epicentre of soil health. It serves as soil conditioner, nutrient source, food materials to soil microbes, preserver of environment and a major determining factor for sustaining agricultural productivity in a region⁹. The SOC concentration in most of the Indian

cultivated soils is less than 5 g/kg compared with 15 to 20 g/kg in uncultivated soils due to continuous heavy ploughing operations, removal of crop residues and other bio-solids, and incessant mining of soil fertility¹⁰. Over a period, application of excessive tillage, use of heavy machinery, removal of crop residues and low organic matter (OM) turnover are mainly responsible for deterioration of soil health parameters. Stock of SOC in agro-ecosystems act as a carbon sink, sequester the ambient carbon and help to mitigate climate change^{11,12}. It also promotes macro-aggregates formation, improves physical protection of organic carbon and thus, has positive effects on soil quality^{13,14}.

Several studies showed that CA systems increase the organic matter due to the addition of crop residues which improved the nutrient reserves for plants mostly for all major nutrients, *i.e.* nitrogen¹⁵, phosphorus¹⁶, potassium¹⁷, calcium¹⁸, magnesium¹⁹, zinc²⁰ and manganese¹⁹. Besides this, reduced tillage practices or no tillage under CA system reduce the loss of nutrients through runoff or nutrients adsorbed in sediments lost during water erosion²¹. Adoption of CA practices contribute to increases in SOC, macro-aggregates and soil quality index (SQI) over a period. Regardless of cropping system, the CA practices exhibit better aggregation, SQI parameters in the top soil compared to sub soil layers²². Under the scarcity of crop residues, green manuring is also a viable option for enhancing the carbon pools, hydrolytic enzymatic activities and ecosystem functions²³. CA-based diversified cropping system improves the activity of dehydrogenase and alkaline phosphatase activity in soil which mediate the SOM decomposition, transformation, and mineralization rate²⁴. It plays a pivotal role in decomposition and nutrient cycling many folds compared to the traditional cropping system under conventional tillage. A greater amount of residues stored in the soil with CA systems doesn't always lead to a greater availability of nutrients for crop plants. Because, the nature of crop residues and their management has a significant influence on the plant nutrient availability in soils. Addition of legume residues having low C/N ratio results into faster mineralization and release of N whereas, cereal residues of high C/N ratio temporarily immobilize and impair N availability during the decomposition process^{25,26}. Appropriate soil management through crop residue retention under minimum tillage can improve the biological soil quality index and crop productivity²⁷.

Crop diversification increases the soil microbial diversity and their population because of numerous root exudates which ultimately help in nutrient mineralization and their availability²⁸. Soybean and wheat residues under zero tillage improved soil organic carbon, microbial biomass carbon (MBC), physico-chemical and biological properties of soil, and nutrient status in soil²⁹. Cover crops or intercrops with deep-rooted plants reduce nutrient loss, maintain nutrients equilibrium in root zone and return them to the soil surface *via* mulch or as green manure³⁰. The CA practices by using cover crops, diversifying crop rotations, and reducing tillage also reduce 65-70% of NO₃-N loss through leaching³¹. In a study in Italy, CA practices had lower NO₃-N concentrations below the maximum rooting zone compared to conventional agricultural practices³². Soil enzymatic functions change with cropping system and the degree of soil disturbance³³. The CA as an alternative to enhance productivity and food security while, preserving natural resources and reducing the negative externalities of traditional agricultural practices, have been documented in several studies³⁴. However, the impact of CA systems on soil health has special and temporal variations³⁵. Thus, ecosystem-specific CA practices need to be developed to realize its benefits to improve the soil health and crop productivity³⁶⁻³⁸.

Indian mustard, a dominant and versatile oilseed crop of India, needs system-based approaches at appropriate scale to exploit the yield potential with sustainability while, conserving or rather improving the natural resources and their quality. Oilseeds are the second largest commodity in Indian food economy after the cereals, barely meet 50% domestic edible oil requirement. Oilseeds often cultivated in rainfed conditions under limited resources (biophysical and socio-economic), poor soil health and scarcity of irrigation water resulting into low yield levels³⁹. Thus, there is need to increase the oilseeds production per unit area, time and input without affecting soil and environmental quality. CA-based sustainable intensification of the traditional fallow-mustard system in the rainfed ecology holds promises to address the shortfall of edible oil in the country.

In this backdrop, long term field experiments were conducted for five-years to see the interactive effects of different tillage practices, crop residue re-cycling and mustard based cropping systems on SOC, MBC, soil enzymes, different N fractions, available P and K under semi-arid climates.

Material and methods

Experimental site

The experiment was conducted for 5-years (2016-17-2020-21) at the research farm of Indian Council of Agricultural Research (ICAR)-Directorate of Rapeseed-Mustard (DRMR)(77°3' E, 27°15' N), Bharatpur, India. The climate is semi-arid characterized with wide range of temperature between summer and winter. The maximum temperature during the mustard growing season fluctuated between 20.5 in January to 36.3 °C in October, and minimum temperature between 7.0 °C January to 27.4 °C in July. The rainfall mostly (75%) received during the south-west monsoon (July-September). The soils were poor in organic carbon (2.4 g kg⁻¹) and available N (126.3 kg ha⁻¹); whereas, medium in 0.5N NaHCO₃ extractable P (17.2 kg ha⁻¹) and 1N NH₄OAc exchangeable K (149.3 kg ha⁻¹). The texture is sandy clay loam with bulk density 1.52 Mg m⁻³.

Treatment details and agro-techniques

The treatment comprised of three-tillage and crop residue re-cycling [permanent beds with residue (PB+R); zero tillage with residue (ZT+R), and conventional tillage without residue (CT-R)] in main-plots, and six-oilseed brassica-based cropping systems [fallow-mustard (F-M), cluster bean (*Cyamopsis tetragonoloba* L.)-mustard (CB-M), green gram (*Vigna radiata* L.)-mustard (GG-M), maize (*Zea mays* L.)-mustard (Mz-M), pearl millet (*Pennisetum glaucum* (L.) R. Br.)-mustard (PM-M), and sesame (*Sesamum indicum* L.)-mustard (S-M)] in sub-plots. Thus, in total 18 interactions were allocated in the split-plot design after randomization, and replicated three times in the permanent plots (suppl. file 1). Best crop management practices were followed in all the treatments. System-wise residue retained were; 2.3, 2.5, 3.8, 4.2, 3.1, and 2.7 Mg ha⁻¹ in PB+R; and 2.4, 2.4, 3.7, 3.7, 3.3 and 2.3 Mg ha⁻¹ in ZT+R under F-M, CB-M, GG-M, Mz-M, PM-M, and S-M systems, respectively (suppl. file 2). Both dry as well as rainy season crops were optimally nourished with their respective recommended doses of macro and micronutrients except 20% additional N applied to PB and ZT plots in Indian mustard.

Collection of plant material if any, comply with relevant institutional, national, and international guidelines and legislation in the present study.

Soil sampling and analysis

Soil samples were collected from each plot at 0–15 and 15–30 cm depth by an auger with 5 cm diameter at 30 and 60 days after sowing (DAS), and at harvest of mustard crop at the completion of five years. Samples were collected from three locations within each plot and a composite sample was prepared by mixing them. A part of the fresh soil samples were kept in a refrigerator at 4°C for analysis of soil biological parameters. *viz.*, microbial biomass carbon (MBC), dehydrogenase activity (DHA) and alkaline phosphatase activity (AIP). The remaining portion of the soil samples were air-dried in shade, ground to pass through a 2-mm sieve, stored in plastic jar for analysis of soil chemical properties *viz.* SOC, available N, nitrate-N, total-N, available P and available K. The SOC was estimated by Walkley and Black method⁴⁰, and MBC by fumigation method⁴¹. The N fractions were estimated using methods like; alkaline potassium permanganate for available N⁴², steam distillation for nitrate N⁴³ and microkjeldahl digestion method for total N⁴⁴. The available P in soil was determined by spectrophotometer using 0.5 M NaHCO₃ extractant at pH 8.5⁴⁵. Available K in soil was determined by flame photometer using 1 N neutral ammonium acetate extractant⁴⁶. Hydrolytic enzyme dehydrogenase (μg TPF g⁻¹ soil 24 h⁻¹) was estimated using triphenyl tetrazolium chloride substrate⁴⁷, and alkaline phosphatase (μg PNP g⁻¹ h⁻¹) by p-nitrophenol⁴⁸.

Statistical analysis

The data were recorded for different parameters such as SOC, MBC, DHA, alkaline phosphatases, N fractions and available P and K under different tillage and mustard based cropping systems and statistically analyzed using analysis of variance for split-plot design online data analysis Portal⁴⁹. The F-test was used to determine the least significant difference (LSD) at $p=0.05$ among the main and sub-plot treatment effects of the tillage systems and cropping systems.

Results

Soil organic and microbial biomass carbon under different managements

Soil organic carbon content increased significantly ($p<0.05$) with CA practices (PB+R and ZT+R) compared to the CT-R practices and that to in the rhizosphere soil (Table 1). The PB+R practice improved organic carbon by 19 and 57% in top soil and 14 and 35% in sub soil (15-30 cm) at 30 DAS compared to ZT+R and CT-R, respectively. Comparison with the rest of the practices, ZT+R also increased organic carbon content markedly at 30 DAS over the CT-R by 32% in top soil and 19% in sub soil. The PB+R being on par with ZT+R recorded markedly higher organic carbon content at 60 DAS by 14% in top soil and 15% in sub soil over the CT-R. At harvest, organic carbon content didn't influence significantly ($p<0.05$) due to different tillage and residue management practices; however, PB+R practice was recorded highest with an increment of 11 and 9% in top soil and sub soil layers over the CT-R, respectively.

Table 1. SOC (%) at different crop stages in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	0.69	0.58	0.79	0.78	0.60	0.58
ZT+R	0.58	0.51	0.74	0.72	0.57	0.55
CT-R	0.44	0.43	0.69	0.68	0.54	0.53
LSD ($p=0.05$)	0.06	0.05	0.06	0.07	NS	NS
Cropping systems						
F-M	0.46	0.42	0.69	0.67	0.53	0.50
CB-M	0.61	0.57	0.77	0.76	0.60	0.58
GG-M	0.70	0.57	0.79	0.79	0.60	0.59
Mz-M	0.59	0.51	0.76	0.73	0.59	0.58
PM-M	0.57	0.51	0.73	0.71	0.58	0.54
S-M	0.49	0.46	0.71	0.69	0.54	0.52
LSD ($p=0.05$)	0.03	0.04	0.06	0.06	0.04	0.04

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Indian mustard based cropping systems significantly influenced soil organic carbon content and recorded highest in GG-M system in top soil and sub soil at all the crop stages (30 and 60 DAS, and at harvest) depicted in Table 1. GG-M cropping system increased organic carbon content by 52%, 14%, 13% in top soil and 36%, 18% and 2% in sub soil at 30 and 60 DAS and at harvest over the F-M system, respectively. Organic carbon content increased from 30 to 60 DAS in all the cropping systems, however, recorded significantly lower values at harvest stage.

Soil microbial carbon significantly ($p<0.05$) increased with CA practices (PB+R and ZT+R) compared to CT-R practices upto 30 cm soil depth in the crop season (Table 2). At 30 DAS, PB+R

recorded MBC 128 mg/kg in surface soil and 123 mg/kg in sub soil. These values were higher by 11% and 27% in top soil, and 12 and 34% in sub soil over the ZT+R and CT-R, respectively. The ZT+R also increased MBC at 30 DAS by 14 % and 20% in top soil and sub soil layer over the CT-R, respectively. With growing crop period upto 60 DAS, MBC increased by 10% and 26% in top soil, and 10 and 31% in sub soil with the PB+R over the ZT+R and CT-R, respectively. MBC also increased with ZT+R by 14% and 19% in top soil and sub soil layer at 60 DAS, respectively. At harvest, PB+R recorded higher MBC by 9 % and 18% in top soil, and 8 and 22% in sub soil over the ZT+R and CT-R, respectively. The ZT+R also increased MBC at harvest by 8% in top soil and 12% in sub soil layer over the CT-R, respectively. It also observed that different cropping systems were affected the MBC in soil at different crop stages. Legume based cropping systems (GG-M and CB-M) recorded the higher soil MBC compared to conventional cropping system (F-M). The GG-M system showed better productivity of microbial count and recorded MBC 146 mg/kg in surface soil and 124 mg/kg in sub soil at 30 DAS. However, at further crop stages recorded lower amount of MBC than 30 DAS. MBC content increased by 46%, 30% and 29% in top soil; whereas, 31%, 23% and 22% in sub soil at 30 and 60 DAS and at harvest in the GG-M cropping system over the F-M system, respectively.

Table 2. MBC (mg/kg) at different crop stages in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	128	123	123	118	104	79
ZT+R	115	110	112	107	95	73
CT-R	101	92	98	90	88	65
LSD (p=0.05)	12	5	5	6	5	5
Cropping systems						
F-M	100	95	104	100	85	69
CB-M	135	113	120	115	98	81
GG-M	146	124	135	123	111	84
Mz-M	115	110	118	112	97	73
PM-M	115	105	109	106	93	71
S-M	102	101	105	104	88	70
LSD (p=0.05)	9	6	7	5	8	7

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Dehydrogenase (DHA) and alkaline phosphatase (ALP) activity under different managements

Dehydrogenase enzyme activity in soil increased significantly under CA practices (PB+R and ZT+R) compared to CT during the crop season upto 30 cm soil depth (Table 3). The PB+R increased DHA at 30 DAS by 23 and 41% in top soil, and 19 and 36% in sub soil over the ZT+R and CT-R, respectively. The ZT+R also increased DHA markedly at 30 DAS over the CT-R by 15% in top soil and 14% in sub soil. DHA activity increased with increasing crop duration. At 60 DAS, the PB+R increased DHA over ZT+R and CT-R by 6 and 26% in top soil, and 23 and 30% in sub soil, respectively. At 60 DAS, DHA also increased 63% in surface and 53% in sub soil in ZT+R plots over CT-R. At harvest, PB+R being at par with ZT+R, significantly enhanced the DHA level 10% in top soil and 15% in sub soil over the CT-R. ZT+R also increased DHA significantly at harvest by 10% in top soil and 13% in sub soil over the CT-R.

Table 3. Effect of tillage, crop residue and mustard-based cropping systems on DHA ($\mu\text{g TPF/g soil/24 h}$) at different crop stages after 5-years under different.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	58	57	67	65	54	53
ZT+R	47	48	63	53	54	52
CT-R	41	42	53	50	49	46
LSD ($p=0.05$)	3	3	4	3	3	3
Cropping systems						
F-M	40	34	44	53	39	37
CB-M	55	56	72	60	61	59
GG-M	58	57	79	67	68	61
Mz-M	53	60	69	58	54	58
PM-M	46	47	52	51	47	50
S-M	40	41	49	48	44	41
LSD ($p=0.05$)	5	4	6	4	4	5

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

In cropping systems, secretion of root exudates directly enhanced the soil microbial count and population (Table 4). It mediated the DHA activity and plant nutrient kinetics in soil. In this experiment, legume based cropping systems significantly ($p<0.05$) increased DHA at both the soil layers in the crop season compared to other systems. The highest DHA was recorded in GG-M system at 30 and 60 DAS and at harvest which was higher by 45, 80 and 74% in top soil, and 68, 26 and 65% in sub soil over the F-M system, respectively.

Table 4. Alkaline phosphatase ($\mu\text{g PNP/g soil/24 h}$) at different crop stages in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	24	20	88	84	77	65
ZT+R	22	16	83	73	72	53
CT-R	20	13	70	64	64	50
LSD ($p=0.05$)	2	1	4	4	4	3
Cropping systems						
F-M	15	12	61	56	55	50
CB-M	22	15	85	70	71	60
GG-M	25	20	111	107	85	67
Mz-M	23	18	83	80	83	58
PM-M	22	17	87	81	69	51
S-M	19	15	62	49	52	48
LSD ($p=0.05$)	2	1	6	4	5	4

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Alkaline phosphatase enzyme activity in soil recorded significantly higher in PB+R compared to ZT+R and CT-R (Table 4). The PB+R improved alkaline phosphatase activity at 30 DAS over the ZT+R and CT-R by 9 and 20% in top soil, whereas, 25 and 54% in sub soil, respectively. However, the ZT+R also significantly increased alkaline phosphatase by 10% in top soil and 23% in sub soil over the CT-R. At 60 DAS, PB+R improved alkaline phosphatase activity over ZT+R and CT-R by 6 and 26% in top soil, and 15 and 31% in sub-soil, respectively. Alkaline phosphatase activity also increased significantly ($p < 0.05$) at 60 DAS with ZT+R by 19% in top soil and 14% in sub soil. Similarly at crop harvest stage, alkaline phosphatase activity increased with PB+R over the ZT+R and CT-R by 7 and 20% in top soil, and 23 and 30% in sub soil, respectively. The ZT+R also improved alkaline phosphatase activity at harvest by 13% in top soil and 6% in sub soil over the CT-R. Legume based cropping system GG-M recorded the highest alkaline phosphatase activity at both the soil layers during the crop season compared to the other cropping systems. GG-M improved alkaline phosphatase activity by 67, 82 and 55% in top soil, and 67, 91 and 34% in sub soil at 30 and 60 DAS, and at harvest, respectively.

Tillage and crop residue management practices markedly influenced the soil available N content at 30 and 60 DAS, however, didn't affect significantly ($p < 0.05$) at harvest stage (Table 5). At 30 DAS, PB+R increased soil available N significantly in top soil (0-15 cm) over ZT+R and CT-R by 35%, however, ZT+R showed no significant difference with CT-R. In sub soil (15-30 cm), PB+R recorded higher soil available N compared to ZT+R (12%) and CT-R (31%). The ZT+R also increased available N significantly in sub soil over the CT-R (17%) at 30 DAS. At 60 DAS, PB+R increased soil available N content over the ZT+R and CT-R by 7 and 69% in top soil, and 20 and 80% in sub soil, respectively. At 60 DAS, the ZT+R practice also increased available N content in soil over CT-R by 58% in top soil and 50% in sub soil. Though, the tillage and residue management practices couldn't influence available N content at harvest but, recorded maximum in PB+R. Among the different cropping systems, GG-M showed higher available N content during all the crop growth stages at 0-15 and 15-30 cm depth. GG-M system increased available N content by 23, 95 and 11% in top soil, and 5, 127 and 9% in sub soil at 30 and 60 DAS and at harvest, respectively.

Table 5. Soil available-N (kg/ha) at different crop stages in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	58	47	61	54	189	185
ZT+R	43	42	57	45	187	183
CT-R	43	36	36	30	182	174
LSD ($p=0.05$)	1	2	4	4	NS	NS
Cropping systems						
F-M	43	43	41	30	175	175
CB-M	48	39	69	52	182	179
GG-M	53	45	80	68	194	191
Mz-M	48	41	44	35	194	182
PM-M	49	42	36	34	193	181
S-M	47	38	40	37	178	176
LSD ($p=0.05$)	4	4	5	3	11	10

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Soil nitrate-N content improved significantly ($p < 0.05$) with the CA practices (PB+R and ZT+R) in both the soil layers during the crop season compared to CT-R practices (Table 6). The PB+R increased

nitrate N over the ZT+R and CT-R at 30 DAS by 9 and 20% in top soil, and 7 and 19% in sub soil, respectively. The ZT+R also increased nitrate N at 30 DAS by 10 and 12% in top soil and sub soil, respectively. At 60 DAS, PB+R accumulated soil nitrate N content over ZT+R and CT-R by 7 and 24% in top soil, and 9% and 20% in sub soil, respectively. Soil nitrate N also increased markedly at 60 DAS with ZT+R by 16% in top soil and 10% in sub soil over the CT-R. At harvest, PB+R reported at par with ZT+R improved soil nitrate-N significantly over CT-R by 16% in top soil and 11% in sub soil. The ZT+R also increased soil nitrate N at harvest over the CT-R by 14% in top soil and 8% in sub soil layer. Cropping systems positively influenced the soil nitrate N and recorded highest in GG-M system in both the soil layers (0-15 and 15-30 cm) at all the stages from 30 DAS to harvest. The GG-M increased nitrate N by 9, 28 and 8% in top soil, and 7, 19 and 16% in sub soil at 30 and 60 DAS, and at harvest, respectively.

Table 6. Soil nitrate-N (kg/ha) at different crop stages in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	36	31	31	24	43	42
ZT+R	33	29	29	22	42	41
CT-R	30	26	25	20	37	38
LSD (p=0.05)	3	2	2	1	2	3
Cropping systems						
F-M	33	29	25	21	39	37
CB-M	35	28	30	23	40	43
GG-M	36	31	32	25	42	43
Mz-M	36	29	29	21	41	41
PM-M	33	29	28	21	40	39
S-M	26	25	27	20	40	39
LSD (p=0.05)	3	3	3	2	2	2

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Total soil N content significantly ($p < 0.05$) increased with PB+R and ZT+R compared to CT-R, and recorded highest (1147 kg/ha in sub soil) in PB+R practice (Table 7). The PB+R increased total soil N at 30 DAS by 20 and 38% in top soil, and 34% and 48% in sub soil compared to ZT+R and CT-R, respectively. ZT+R also increased total soil N over the CT-R by 15% in top soil and 25% in sub soil layer at 30 DAS. At 60 DAS, PB+R markedly increased total soil N over the ZT+R and CT-R by 10 and 26% in top soil, and 13 and 24% in sub soil, respectively. The ZT+R also improved total soil N over the CT-R by 18% in top soil and 14% in sub soil layer. It was also observed that the higher amount of total N measured in surface soil at 30 and 60 DAS, whereas, at harvest sub soil showed higher amount of total N than in surface soil. Among cropping systems, GG-M recorded highest total soil N content compared to other systems at both the soil layers during the crop season. GG-M system increased total N content by 45, 55 and 36% in top soil, and 130, 37 and 46% in sub soil at 30 and 60 DAS, and at harvest, respectively.

Table 7. Soil total-N (kg/ha) at different crop stages in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Crop stage					
	30 DAS		60 DAS		At harvest	
	Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue						
PB+R	941	617	1110	871	1134	1147
ZT+R	784	460	1008	772	1072	1084
CT-R	684	368	882	702	910	947
LSD (p=0.05)	80	56	60	61	47	83
Cropping systems						
F-M	687	299	774	672	896	849
CB-M	871	647	1085	821	1089	1075
GG-M	996	687	1202	921	1215	1237
Mz-M	821	526	1070	796	1117	1065
PM-M	747	448	983	772	995	1045
S-M	697	383	886	747	920	886
LSD (p=0.05)	65	37	54	56	79	65

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Available-P content in soil influenced significantly ($p < 0.05$) with the CA practices (PB+R and ZT+R) and recorded highest in PB+R practice (Table 8). The PB+R increased available P content over the ZT+R and CT-R by 17 and 9% in top soil, and 27 and 22% in sub soil, respectively. The ZT+R also improved soil available P by 9% in top soil and 22% in sub soil over the CT-R. Among the cropping systems, GG-M recorded the highest soil available P which was 29 and 37% higher in top soil and sub soil layer over the F-M system, respectively. The GG-M, Mz-M and PM-M showed at par value of available phosphorus in top soil, whereas, sub soil samples had different values. Lower available P was measured in sub soil samples as compared to surface soil. Available K content was also measured at harvest and found that K content increased markedly with PB+R (upto 319 kg/ha) at the end of 5-year experiment compared to CT-R (270 kg/ha). The PB+R being at par with ZT+R increased available K by 16 and 18% in top soil and sub soil over the CT-R, respectively. Legume based cropping systems (GG-M and CB-M) recorded markedly higher available K in soil compared to conventional cropping system (F-M). The GG-M increased soil available K by 28 and 23% in top soil and sub soil layer over the F-M, respectively.

Table 8. Soil available-P and K (kg/ha) at harvest in top (0-15 cm) and sub soils (15-30 cm) after 5-years under different tillage, crop residue and mustard-based cropping systems.

	Available P		Available K	
	Top soil	Sub soil	Top soil	Sub soil
Tillage and crop residue				
PB+R	14	14	274	319
ZT+R	12	11	275	296
CT-R	11	9	236	270
LSD (p=0.05)	1	1	20	26
Cropping systems				
F-M	10	9	227	264
CB-M	12	11	277	314
GG-M	13	12	291	326
Mz-M	13	12	277	290
PM-M	13	11	258	284

S-M	12	11	239	272
LSD (p=0.05)	1	1	15	22

DAS: Days after sowing, F-M: Fallow-Mustard, CB-M: Cluster bean-Mustard, GG-M: Green gram-Mustard, Mz-M: Maize-Mustard, PM-M: Pearl millet-Mustard, S-M: Sesame-Mustard, PB: Permanent bed, ZT: Zero tillage, CT: Conventional tillage.

Discussion

Soil organic carbon is an indicator of soil health and mediate the plant nutrient dynamics in soil. In the present study, no-till permanent beds with crop residue re-cycling (PB+R) accumulated more SOC throughout the crop season compared to other practices. It could be due to constant crop residue addition under no soil disturbance condition in permanent beds. CA practices (zero tillage and residue re-cycling) increased SOC by increasing organic carbon inputs to the soil (plant residues) and by reduction in SOC losses through oxidation and erosion^{10,50}. The SOC under no disturbance condition might have also locked the organic C molecules into long lived soil aggregates and retained as permanent C pool. Residues of previous crops gets added, decomposed and mineralized with the time span and thus, reached at peak at the 60 DAS showing maximum SOC content in soil in the present study. It might also be due to higher diverse microbial population which can easily mineralize SOM, resulting into higher active C pools without affecting recalcitrant pool in the residue-amended plots. Other workers have also reported that fresh crop residues end as a continuous source of food materials for the soil biota and which convert it into labile fraction of OC^{51,52}. The priming effect of OC enhanced the soil aggregation stability, water holding capacity and physico-chemical properties of soils which ultimately improved soil health and productivity⁵³.

The SOC content varies with the soil depth due to variation in soil texture, structure and quality of crop residues. The fractions of SOC present in dissolved form are susceptible to leaching and found more into lower soil profiles. Therefore, to obtain a more accurate assessment of CA practices' impact on SOC, the entire plow depth should be sampled and analysed⁵⁴. SOC content was found more in the top soil (0-15 cm) than in the sub soil (15-30 cm) in the CA plots compared to CT plots in the present study. More availability of plant root exudates and microbial population in surface soil could be the reason of more accumulation of labile C fraction in top soil. Further, the rate of accumulation of C content could be enhanced in top soils due to minimum soil disturbance and continuous enrichment of crop residues under the conservation tillage practices. Though, the variation in SOC storage in different plow layers in CA practices also depends on various factors such as the quantity and quality of plant residues, time period and edaphic-climatic characteristics⁵⁵. The top soil is active sheet for biological activities where the effects of management practices can be imitated easily^{56,57}. Other workers also reported that CA practices increased the SOC stock in 30 cm soil layer compared to conventional agriculture practices⁵⁸. In maize-mustard rotation, CA systems keenly showed effects on SOC in 0-15 cm and 15-30 cm soil depths while at 30-45 cm, there were no significant differences⁵⁹. It was reported that no-tillage and reduced tillage systems with residue retention increased SOC stock by 13 and 12% in comparison to CT practices, respectively⁶⁰. Due to decreased exposure to air, accumulated SOC at 30 cm soil depths have a lower likelihood of oxidation-mineralization and is therefore anticipated to have a longer residence duration⁶¹. The overall effect of CA on SOC accumulation in the plough layer (0-30 cm) was 12% higher in comparison to conventional agriculture which corresponds to a carbon increase of 0.48 Mg C/ha/year. However, the effects were variable depending on the SOC content under conventional agriculture; it was 20% in soils which had ≤ 40 Mg C/ha while, it was only 7% in soils that had >40 Mg C/ha⁶². Thus, soils having less than 40 Mg C/ha stocks should be targeted with added residue biomasses in a CA rotation to enrich the SOC. The soils of the current study site were having ≤ 10 Mg C/ha⁶³ that might be the possible reason of CA practices showing significant response to SOC increment compared to CT practices under semi-arid rainfed ecology. The effect of CA on SOC also depends on soil clay content, pH, EC, heavy metal and moisture etc⁶². Increase or decrease in SOC content depends on decomposition and mineralization processes which are largely governed by dynamic soil and climatic parameters. These

processes also affected by the priming effects of crop residues in CA practices, and mineral nitrogen and other nutrients in CT system⁶⁴.

Legume based cropping systems (green gram-mustard/cluster bean-mustard) recorded higher organic carbon compared to cereal/oilseed based systems in the present study. The highest organic carbon content was found in green gram-mustard cropping system where SOC increased by 13-52% in top soil (0-15 cm) and 2-36% in sub soil (15-30 cm) over the traditional fallow-mustard system. SOC recorded higher in green gram-mustard cropping system might be due to green gram, being a legume crop and addition of easily decomposable residue of low C/N ratio in soil compared to other crops. Legume crops inject elemental N into organic bound N, increase plant biomass and organic root exudates which indirectly enhance the SOC content⁶⁵. Moreover, addition of residues having varying C/N ratio under no till system also affect the mineralization/immobilization cycle of nutrients, especially N and thus, SOC content varied^{66,67}.

Microbial biomass carbon reflects the ability of soils how well is, and it can accumulate and cycle the essential plant nutrients and soil organic matter (SOM)⁶⁸. Soil microbial biomass carbon in the present study markedly increased with CA practices (PB+R and ZT+R) compared to CT practices upto 30 cm soil depth but, higher in 0-15 cm depth throughout the crop season. Data indicated that addition of residues helped to increase MBC, which is also considered as one of the labile pools of SOC. Our findings are in conformity that more amount of organic fractions improve more microbial population and their diversity in the soil which ultimately increase the MBC⁶⁹. In CA practices, more aeration in top soil might have increased mineralization of SOM and thus, increased soil microbial biomass carbon, nitrogen and microbial quotient⁷⁰. Our findings revealed that MBC recorded highest at 30 DAS in top soil, and thereafter showed decreasing trend till harvest as well as in the sub soil layers could be due to more availability of fresh and decomposable crop residues at surface soil in the initial days. Other workers also reported that residue retention significantly increased MBC in the surface soil layer than the no residue treated plots under long-term plots which had significant effect on MBC^{71,72,73}. Legume-based green gram-mustard cropping systems recorded highest soil MBC compared to conventional fallow-mustard cropping system in the present study because the legume crops might have favoured more root exudates and rhizospheric microbial population. Similar studies in pigeon pea+soybean intercropping system under conservation tillage systems showed significantly higher SMB-C and SMB-N levels than CT without crop residues⁷⁴.

Monitoring of enzyme activity in a soil is essential to know the potential of the soil to perform different biochemical processes to maintain soil fertility vis-a-vis soil quality⁷⁵. Enzyme activities are also good indicator of decomposition potential of organic C and plant nutrients, and thereby nutrients availability to plants. The CA-based practices significantly influenced the soil enzymes such as DHA and alkaline phosphatase in the present study. Dehydrogenase enzyme activity in soil also increased significantly under CA practices (PB+R and ZT+R) compared to CT practices during the crop season upto 30 cm soil depth could be due to better aeration, more reaction period and positive growth of the soil biota under CA practices⁷⁶. The results showed that soil enzyme activity and nutrient concentration were strongly impacted by tillage intensity, soil depth, and growth phases in present study. High concentration of crop residues along with the roots of previous crops on surface soil affects integral microbial activities to a wider extent under undisturbed soils. The secretion of root exudates under the favorable condition of soil root ecology accelerated the microbial biomass carbon might be a crucial factor under CA management compared to CT systems⁷⁷. The long term supply of C through the different residue management practices are supposed to accelerate the soil microbial count and diversity mediated the greater enzyme activity compared with no residue plots⁷⁸. Significant interactions were observed between different management practices and enzyme activities under CA management directed positive improvement in soil enzyme activities⁷⁹. It helping in mineralization of SOM, improving nutrient cycling, formation of soil aggregates which leads to the higher production of crop yield⁸⁰. Augmentation in microbial biomass, more substrate availability, minimum soil disturbance, improved soil aggregated structures might have increased the soil enzymes activity under a CA based cropping systems compared to CT^{59,81}. On the other hand, there was a reduction in soil biological activities under CT due to intensive tillage operations coupled with

lesser availability of fresh crop residues in rice-wheat cropping system on an alluvial soil⁸². Whereas, partial CA in cereal-based systems exhibited higher DHA activity measured in Indo-Gangatic plain of India⁸¹.

In this experiment, DHA and alkaline phosphatase had been increased maximum from 30 to 60 DAS and slightly declined at harvest, and more in the top soil than in sub soil. In similar way, DHA and alkaline phosphatase activity in soil were reported higher at maximum tillering in rice-based CSA systems over maize-based systems³⁹. Further, the higher acid phosphatase activity in bulk soils at maximum tillering stage of rice and flowering stage of maize system is reported due to differential residue decomposition leading to varying rates of labile carbon release in these systems³⁹. Further, the maize residues applied to the soil's surface decomposed more quickly than rice, and wheat residues, as well as mixes of those residues applied to the soil's surface⁸¹. Studies reported that soil biological indicators were higher under no-till and 30% residue retention under bioenergy sweet sorghum in South African marginal soils⁸³. The microorganisms were also higher at rhizosphere zone due to more rhizodeposition of C (54-63 % in cereals) of below ground carbon inputs through roots⁸⁴. Ecto-enzymes produced in large quantities by soil microbes may break down macromolecular organic materials, facilitating the recycling of nutrients and the flow of energy in terrestrial ecosystems¹⁴. Legume based cropping systems significantly improved the DHA at both the soil layers (15 and 30 cm) in the crop season compared to other systems. Moreover, zero tillage, resources (irrigation water, and nutrients) management and suitable crop rotation with mungbean provided habitat for the microbes more hospitable⁸⁵. Decomposition of maize residues releases labile C which was available to microbes and resulted in higher DHA activity^{39, 86}. Association of no-till and crop rotation with mungbean also enhance enzymatic activity in the soil surface^{87,88,89}.

Soil N fractions (available-N, nitrate-N and total-N) increased with CA-based practices and crop residue re-cycling markedly at 30 and 60 DAS of mustard. In this experiment, soil N fractions markedly increased with the green gram-mustard cropping system up to 30 cm soil layers during the crop season compared to other cropping systems. The CA-based no tillage and residue retention helps in improving SOC, aggregation stability, microbial process and soil enzymes activities which modulated the soil mineralization kinetics and increased N availability in soil solution⁹⁰. The SOM is playing a crucial role in soil fertility and sustainability, as it increased soil aggregate stability and water retention and provides a reservoir of essential nutrients for crops⁹¹. In this experiment, N fractions were reported highest amount in green gram-mustard cropping system compared to rest of the cropping systems (Table 2). It might be due to more accumulation of SOM in green gram-mustard cropping system, and induced the mineralization kinetics by enhanced soil microbial population. This process improved the soil N levels in soil solution and might have improved the crop yield potential. These results are in close conformity with that of 9% increase of total N under CA-based rice-wheat system compared to CT⁹². Nitrogen content was more in the top soil could be due to higher N mineralization rates and ammonium to nitrate ratio from intact soil core incubation in CA top-layer compared to deep ploughed soil layers⁹³.

Available P and K content in soil were also highly influenced with the CA practices (PB+R) and also in legume based cropping subsystems at the end of 5-year experiment in top (0-15 cm) and sub soil (15-30 cm) layers. Available P content was found more in the plough layer, however, K content recorded more in the deeper layer. Phosphorus movement in soil reported less and the leaching loss from root zone also lower which might be reason of high P content in top soil⁹⁴. Further, the applied fertilizers and organic P during the crop period accumulated 50% inorganic and 38% organic forms of P in upper soil layer. Furthermore, enhanced SOM with fresh residue retention under CA system with reduced tillage ensures minimal soil mixing of the applied fertilizer with soluble P leading to less chances of fixation, adsorption and followed by precipitation as soluble phosphate-humate complexes, which enhance the lability and availability of soil P^{95,96}. However, under CT, the availability of labile P is reduced due to maximum soil mixing⁹⁷. The potassium is an important plant nutrient found in cationic form subjected to leaching in soil profile in adequate condition. In a study, more than 33% applied K leached into lower profile after 81 days in Brazilian soils⁹⁸. Apart from total K, only 2 to 3 percent of it is accessible to plants in a free soluble form since the majority is still bonded

to SOM, other soil minerals, making up an estimated 95% of soil potassium⁹⁹. Dissolved SOC also enhanced the leaching and immobilization rate of K in lower layer of soil profile¹⁰⁰. The soil available P and K content was more in the maize-mustard system in the present study under the CA practices might be due to that cereal residues supply higher amount of P and K to soil through decomposition as they have higher P and K concentration in their biomass⁶⁶. Besides this, CA practices might have improved availability of soil N, P and K by improving soil aggregation formation and stability, mineralization of SOM, and decreasing soil and nutrient losses from the soil⁵².

Conclusion

Regarding the implementation of CA practices, there are a number of restrictions and challenges that must be addressed in order to increase their adoption on a large scale. This study revealed that medium term conservation agriculture practice (~ 5 years) significantly improved soil fertility with better soil chemical and biological health parameters in the top 0-15 cm soil layer. Addition of legume residue (green gram) along with mustard residues over the years improved soil quality parameters (SOC, MBC, DHA, alkaline phosphatase, N fractions, and available P and K). In nutshell, CA-based no-till PB+R in GG-M cropping system with two crops' residue recycling can be a promising soil fertility management practice in the north-western India, and in similar agro-ecologies of the tropic and sub-tropic regions. This study directed that crop management practices under a specific agro-ecosystem have important implications in nutrient availability to plants. Proper management of crop residue decomposition rate promotes the balance supply of nutrients which could help in savings of precious nutrients applied externally during the crop growth period. Therefore, this study leads the future path of research for considering more efforts on nutrients availability and priming effect of crop residues at different crop growth stages in rhizosphere under CA based oilseed systems.

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