Assessing the impact of residue retention on soil biochemical properties of Vertisols in a Maize-Chickpea cropping system under different tillage practices in Central India

ABSTRACT

This study examined, the potential effect of different residue retention practices on soil biochemical properties in Vertisol of central India. Experimentwas conducted in Randomized Block Design (RBD) with three different levels of crop residue retention (RR); 0%, 30%,90% in maize chickpea cropping system over conventional tillage (CT).The parameters assessed were total organic carbon (TOC), β-glucosidase activity, dehydrogenase activity (DHA), fluorescein diacetate hydrolysis activity (FDA), and stratification ratio. Soil samples were collected from 0–15 cm and 15–30 cm depths at the end of the cropping cycle to evaluate the effects of different residue management strategies. At the surface soil (0–15 cm), TOC was significantly higher under 90% RR (15.24 g kg^{-1}) and 30% RR (12.16 g kg^{-1}) compared to CT (9.39 g kg^{-1}). Enzymatic activities also showed significant improvements with increased residue retention. DHA at 0–15 cm was highest under 90% RR (103.57 µg TPF g^{-1} day^{-1}), followed by 30% RR (84.63 µg TPF g^{-1} day^{-1}) and CT (70.75 µg TPF g^{-1} day^{-1}). A similar trend was observed for FDA, where 90% RR recorded 26.13 µg fluorescein g^{-1} h^{-1}, exceeding CT (22.91 µg fluorescein g^{-1} h^{-1}). β-glucosidase activity was also highest under 90% RR (169.60 µg PNG g^{-1} soil h^{-1}), with reduced values at greater soil depths. Enzymatic activities (β-glucosidase, DHA, and FDA) exhibited a strong correlation ($p < 0.01$) with TOC content and were also strongly correlated, confirming their sensitivity to management practices. Stratification ratios did not vary significantly across residue retention levels, likely due to the high clay content protecting TOC and enzymes. These findings highlight the potential of residue retention to enhance soil health and serve as reliable indicators of soil quality in sustainable croppingsystems.

Keywords: *Residue retention, Tillage, cropping system, Total organic carbon, soil enzymatic activity,*

INTRODUCTION

Crop residue retention is a key element of conservation agriculture (CA), alongside (a) minimal mechanical soil disturbance, (b) permanent soil cover, and (c) crop rotation, as highlighted by Ojeda *et al.* (2015) and Ye *et al.* (2019). Crop residues help mitigate the negative impacts of conventional farming practices and enhance soil quality, facilitating better adaptation to climate-related risks (Das *et al.,* 2020; Thierfelder *et al.,* 2018). Land degradation continues to be a significant global issue, particularly in India, where approximately 44 per cent of the total land area is affected (Bhattacharyya *et al.,* 2015; Mythili & Goedecke, 2016). The incorporation of crop residues enhances soil organic matter (SOM), conserves soil moisture, and fosters biological activity (Huang, Xu, & Chen,2008). Residues, especially from staple crops like maize and chickpea, provide a vital source of organic carbon that can stimulate microbial populations involved in soil carbon cycling. Maize (*Zea mays L.*) is an emerging versatile crop with wider adaptability and photo-insensitivity under different ecological scenarios. It has the potential to address issues such as water scarcity and climate change (Parihar *et al*., 2018). Similarly, chickpea (*Cicer arietinum*), is protein-rich and best among all legume proteins,

with the most production centered in India. Maize-based rotations with improved soil management practices enhanced soil properties (Aulakh *et. Al.,* 2008).

Concerns regarding soil deterioration and quality losses have recently increased the significance of soil quality indices, which enable the evaluation of patterns and modifications in various soil management techniques. The agroecosystem's productivity and sustainability are determined by the quality of the soil. To get empirical data on how conservation techniques impact soil qualities, a residue retention management experiment is consequently required. To ascertain the impact of various soil management strategies, a number of indices that combine the physical, chemical, and biological characteristics of soil have been employed (Doran *et al.* 1994). Analysing soil biological processes is crucial for assessing soil quality. A good short-term predictor of soil biological and biochemical fertility is microbial activity (Melero *et al.,* 2008; Nannipieri *et al*., 1990). Soil enzymes play a crucial role in driving numerous reactions related to the breakdown of soil organic matter, nutrient cycling, and the formation of soil structure. They are also considered indicators of soil health because they respond quickly to changes in soil management practices (Gianfreda *et al*., 1996). The stratification ratio serves as a useful measure for assessing the variation of soil nutrients with depth. The distribution of soil organic carbon across different depths has gained significance due to its role in nutrient retention, boosting biological activity, preventing erosion, and supporting agricultural productivity (Franzluebbers *et al*., 2007).

In this study, we hypothesize that by improving soil microbial activity and soil fertility, residue retention would be beneficial. The total organic carbon (TOC), dehydrogenase (DHA), fluorescein diacetate (FDA), and β-glucosidase in Vertisols of Central India were evaluated using varying levels of residue retention and conventional tillage practice.

MATERIALS AND METHODS

Experimental Site

The study was conducted at the research farm of the Indian Institute of Soil Science (IISS) in Bhopal, India. The experimental site is geographically situated at coordinates 23°18'28.26"N and 77°24'26.00"E, with an elevation of 500 meters above sea level. The area receives an average annual rainfall of 1,146 mm, with more than 80% of it occurring between June and September. The region experiences an average annual air temperature of 25°C and has a generally humid subtropical climate. The summer season starts in the latter half of March and lasts until mid-June, while winter peaks in January, with temperatures occasionally dropping close to freezing at night. The soil at the experimental site is classified as Vertisols (black soils) from the *montmorillonite isohyperthermic* family of typic haplustert, and is characterized by its alkaline nature and distinct swell-shrink properties (Aher *et al.,* 2018).

The experiment was conducted using a Randomized Block Design (RBD), with each treatment replicated five times. Each plot measured 7m × 6m. The treatments included residue retention (RR) of (0%), 30%, and 90% in a maize and chickpea cropping system under zero tillage, and conventional tillage management.Maize variety Nath Samrat 1144 was sown with 55 cm ×15cm spacing in the last week of June, while chickpea variety JG-12 with 27.5 cm × 10 cm spacing in mid-October every year using a zero-tillage seed drill machine (Happy Seeder). A recommended dose of nutrients, namely 120 kg N, 60 kg P_2O_5, and 40 kg K_2Oha^{-1} for maize and 20 kg N, 50 kg P_2O_5, and 40 kg K_2O ha^{-1} for chickpea was uniformly applied to the plots using urea, diammonium phosphate, and muriate of potash, respectively.For effective weed control in maize, a tank mix combination of Tembotrione+ atrazine was applied immediately after sowing followed by post-emergence application of tembotrione at 30 days after sowing to manage weeds. In chickpeas, a combination of imazathyparwas applied immediately after sowing followed by post-emergence application of imazethapyr+ clodinofop at 30 days after sowing to control a broad spectrum of weeds. The maize crop was raised under rainfed conditions while for the chickpea three irrigations including the first after dry sowing under residual

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moisture conditions as the residual moisture was not sufficient to ensure proper crop establishment followed by a second at the vegetative stage and the third at the pod filling stage. After harvesting,the previous crop residueretained in 90%, 30%, and 0% treatment was 6.88 t/ha, 2.29 t/ha and no residue for maize. In the case of the chickpea crop, previous residues retained in 90%, 30%, and 0% treatment was 3.1 t/ha, 1.05 t/ha and no residue.Residueswere chopped and left on the soil surface prior to planting the next crop in each cycle.

Soil Sampling and Chemical Analysis

At the end of the second-year experiment, soil samples were collected from two different depths: 0-15 cm and 15-30 cm, After the harvest of each maize and chickpea crop in 2022-2024. The freshly collected soil samples were passed through a 2 mm sieve and immediately stored in plastic bags, loosely tied to allow proper aeration and prevent moisture loss, at 4°C until microbiological and enzyme activity assessments. The remaining soil was air-dried for chemical analysis, which was conducted within two weeks.

Soil pH and electrical conductivity (EC) were assessed using the 1:2.5 soil-to-water ratio method. The total organic carbon content in the soil was analysed through dry combustion with a TOC analyser.

Soil Enzymatic Analysis

β-glucosidase activity was evaluated following the method of Eivazi and Tabatabai (1988), by incubating soil with p-nitrophenyl β-D-glucopyranoside and measuring p-nitrophenol (PNP) absorbance at 400 nm. Dehydrogenase activity (DHA) was assessed using the procedure described by Thalmann (1968), through soil incubation with 2,3,5-triphenyl-tetrazolium chloride (TTC) and measuring the absorbance of triphenyl formazan (TPF) at 546 nm. Fluorescein diacetate (FDA) hydrolysis was determined based on the method of Adams and Duncan (2001), by incubating soil with fluorescein diacetate and recording fluorescein absorbance at 490 nm.

The stratification ratio for total organic carbon (TOC) and enzymatic activities was determined as the ratio of their values in the surface soil layer (0–15 cm) to those in the deeper layer (15–30 cm), following the method outlined by Franzluebbers (2002). All microbial analyses were performed in triplicate for each sample, and the results were expressed on an oven-dry weight basis.

Statistical Analysis

Statistical analysis was conducted using MSExcel, and the results were reported as mean values. Significant differences between residue retention management practices were determined using the student's t-test at ($p = 0.05$). Analysis of covariance (ANOVA) was performed to evaluate the variability of all parameters for each treatment across different soil depths. A correlation matrix for the various properties was constructed based on Pearson correlation coefficients ($p = 0.05$).

RESULT

Soil Chemical Parameters

At the end of the 2022–2024 cropping season, soil pH, EC, and TOC in residue retention practices were measured at both depths (0–15 cm and 15–30 cm). Across all treatments in both cropping years, the pH and EC of the soil were found to be significant at the surface and non-significant in the subsurface (Table 1). The mean soil pH range at the surface (0–15 cm) ranged from 7.5 to 7.9, with the lowest value (7.5) seen under 90 per cent crop residue retention treatment. Although there was a slight increase in the pH of subsurface soil, however, the residue retention treatments did not noticeably affect this parameter.The average soil EC rangesfrom 0.13 dS/m to 0.23 dS/m at the surface (0-15 cm), with the 90 per cent crop residue retention treatment having the lowest value (0.13

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dS/m). However, the mean values of pH and EC at both depths do not significantly differ in the case of no residue and CT.

The distribution of total organic carbon (TOC) varied under different residue retention (RR) levels and conventional tillage (CT) (Table 1). Residue retention significantly increased the TOC at both 0–15 cm and 15–30 cm soil depths in the maize-chickpea cropping system. The increase in TOC due to residue retention management ranges from 38.4 percent to 10.3 percent at the 0–15 cm depth and 18 percent to 4.2 percent at the 15–30 cm depth. After two years of conservation agriculture, the TOC levels under 90 percent, 30 percent, and 0 percent RR were 38.4 percent, 22.8 percent, and 10.3 percent higher, respectively, than those under CT at the 0–15 cm depth. The TOC values range from 15.24 g kg^{-1} (0–15 cm) to 8.66 g kg^{-1} (15–30 cm) under 90 per cent RR, 12.16 g kg^{-1} (0–15 cm) to 7.88 g kg^{-1} (15–30 cm) under 30 percent RR, 10.47 g kg^{-1} (0–15 cm) to 7.41 g kg^{-1} (15–30 cm) under 0 percent RR, and 9.39 g kg^{-1} (0–15 cm) to 7.10 g kg^{-1} (15–30 cm) under CT. The mean TOC values showed a decreasing trend with increasing soil depth, with the highest TOC concentration recorded at the 0–15 cm depth under 90 percent RR.

Dehydrogenase (DHA), Fluorescein Diacetate (FDA)and β-Glucosidase Activity

Significant variations in DHA were observed in both surface and subsurface soils under different levels of residue retention compared to conventional tillage (CT) (Fig 1). At the 0–15 cm depth, DHA activity ranged from 103.57 to 70.55 µg TPF g^{-1} soil 24 h^{-1}, while at the 15–30 cm depth, it varied from 64.19 to 44.77 µg TPF g^{-1} soil 24 h^{-1}. The increase in DHA ranges from 31.88 percent to 4.14 percent at 0–15 cm and from 30.3 percent to 2.9 percent at 15–30 cm. The DHA levels under 90 percent, 30 percent, and 0 percent RR were 31.8 percent, 19.07 percent, and 4.14 percent higherrespectively, than under CT at the 0–15 cm depth. The DHA values range from 103.57 µg TPF g^{-1} soil 24 h^{-1} (0–15 cm) to 64.19 µg TPF g^{-1} soil 24 h^{-1} (15–30 cm) under 90 percent RR, 87.18 µg TPF g^{-1} soil 24 h^{-1} (0–15 cm) to 53.06 µg TPF g^{-1} soil 24 h^{-1} (15–30 cm) under 30 percent RR, 73.60 µg TPF g^{-1} soil 24 h^{-1} (0–15 cm) to 46.12 µg TPF g^{-1} soil 24 h^{-1} (15–30 cm) under 0 percent RR, and 70.55 µg TPF g^{-1} soil 24 h^{-1} (0–15 cm) to 44.77 µg TPF g^{-1} soil 24 h^{-1} (15–30 cm) under CT. The mean DHA values show a decreasing trend with increasing soil depth, with the highest DHA concentration recorded under 90 percent RR at the 0–15 cm depth. In the subsurface soils, the DHA activity was significantly higher under 90 percent RR, showing a 59.6 percent increase compared to CT.

Statistical analysis revealed a significant effect of the different residue retention (RR) practices on FDA activity (Fig. 1). The FDA activity ranges from 26.13 to 16.27 µg fluorescein g^{-1} soil h^{-1} at the 0–15 cm depth and 11.97 to 8.57 µg fluorescein g^{-1} soil h^{-1} at the 15–30 cm depth. The increase in FDA activity due to RR management ranged from 37.8 percent to 17.2 percent at 0–15 cm and from 28.4 percent to -4.4 percent at 15–30 cm. The FDA activity under 90 percent, 30 percent, and 0 percent RR was 37.8 percent, 12.6 percent, and 17.2 percent higher, respectively than under CT at the 0–15 cm depth. The FDA ranges from 26.13 µg fluorescein g^{-1} soil h^{-1} (0–15 cm) to 11.97 µg fluorescein g^{-1} soil h^{-1} (15–30 cm) under 90 per cent RR, 18.62 µg fluorescein g^{-1} soil h^{-1} (0–15 cm) to 8.81 µg fluorescein g^{-1} soil h^{-1} (15–30 cm) under 30 percent RR, 19.64 µg fluorescein g^{-1} soil h^{-1} (0–15 cm) to 8.21 µg fluorescein g^{-1} soil h^{-1} (15–30 cm) under 0 percent RR, and 16.27 µg fluorescein g^{-1} soil h^{-1} (0–15 cm) to 8.57 µg fluorescein g^{-1} soil h^{-1} (15–30 cm) under CT. The mean FDA values exhibited a decreasing trend with increasing soil depth, with the highest FDA concentration recorded under 90 percent RR at the 0–15 cm depth. In the subsurface (15–30 cm), the FDA activity was significantly higher under 90 percent RR, showing a 28.4 percent increase compared to CT.

The β-glucosidase, a key enzyme in the soil carbon cycle, showed activity levels ranging from 169.6 to 83.7 µg PNP g^{-1} soil h^{-1} in surface and subsurface soils. The increase in β-glucosidase activity due to residue retention (RR) management ranges from 16.7 percent to 12.6 percent at the 0–15 cm depth and 19.9 percent to -4.7 percent at the 15–30 cm depth. At the 0–15 cm depth, the β-glucosidase activity was 16.7 percent, 12.6 percent, and 7.9 percent higher under 90 percent, 30 percent, and 0 percent RR, respectively, compared to conventional tillage (CT). The β-glucosidase

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activity ranged from 169.60 µg PNP g^{-1} soil h^{-1} (0–15 cm) to 104.62 µg PNP g^{-1} soil h^{-1} (15–30 cm) under 90 percent RR, 161.58 µg PNP g^{-1} soil h^{-1} (0–15 cm) to 89.47 µg PNP g^{-1} soil h^{-1} (15–30 cm) under 30 percent RR, 153.36 µg PNP g^{-1} soil h^{-1} (0–15 cm) to 79.99 µg PNP g^{-1} soil h^{-1} (15–30 cm) under 0 percent RR, and 141.29 µg PNP g^{-1} soil h^{-1} (0–15 cm) to 83.75 µg PNP g^{-1} soil h^{-1} (15–30 cm) under CT. The mean β-glucosidase activity showed a declining trend with increasing soil depth. The highest activity was recorded at the 0–15 cm depth under 90 percent RR. At the subsurface level (15–30 cm), the β-glucosidase activity was significantly higher under 90 per cent RR, with a 19.9 percent increase compared to CT.

No significant differences were observed in the stratification ratios of TOC and enzymatic activities between the different residue retention levels and CT treatments (Fig 2). Generally, enzymatic activities (β-glucosidase, DHA, and FDA) exhibited a strong correlation ($p < 0.01$) with TOC content and were also strongly correlated (Table 2).

Table1. Mean value of pH, electrical conductivity (EC) and total organic carbon (TOC) in soil under different Residue Retention (RR) levels and Conventional tillage (CT) at different depths.

		Residue Retention				
Soil parameters	Soil depths (cm)	RR-0%	RR-30%	RR - 90 %	CT	C.D value (p=0.05)
pH	0-15	7.81	7.64	7.54	7.92	0.19
	15-30	7.74	7.64	7.54	7.87	N/S
EC (dS m^{-1})	0-15	0.23	0.19	0.13	0.23	0.02
	15-30	0.15	0.14	0.15	0.15	N/S
TOC (g kg^{-1})	0-15	10.47	12.16	15.24	9.39	2.74
	15-30	7.41	7.88	8.66	7.10	1.05

RR- residue retention, CT- conventional tillage

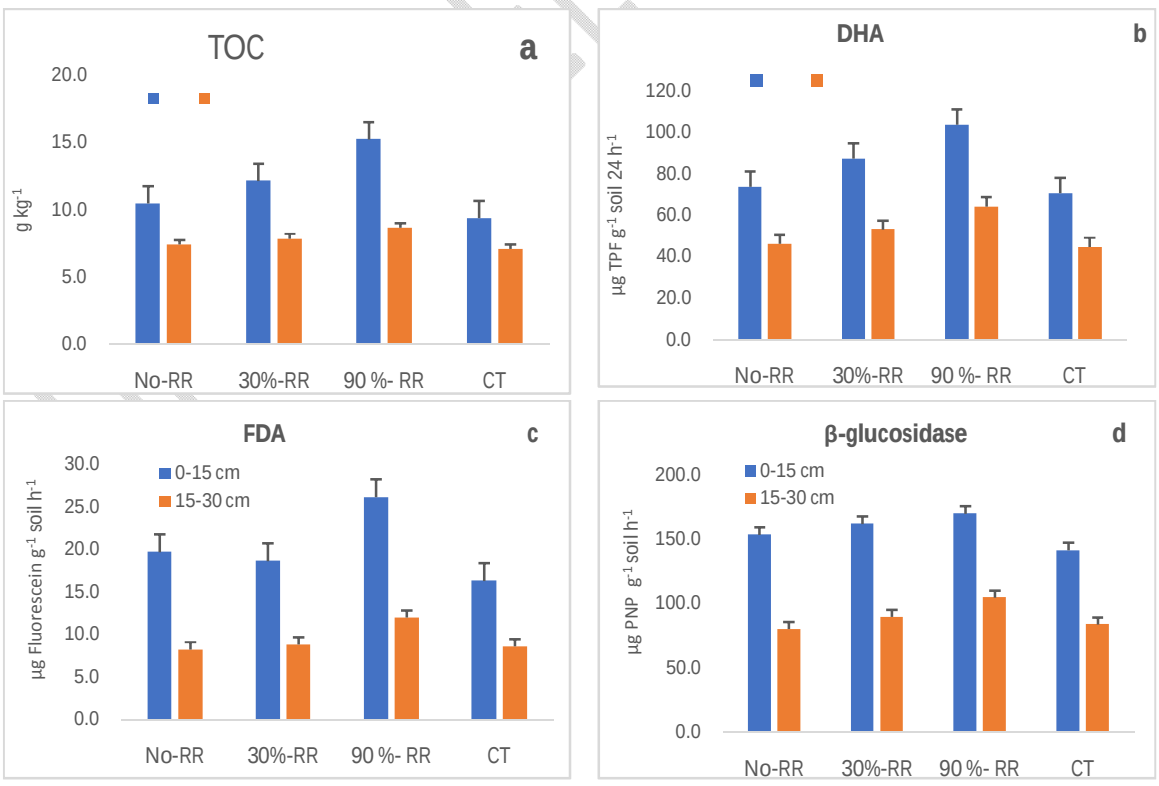

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Figure 1. (a) Total organic carbon (TOC), (b)Dehydrogenase activity(DHA) (c)Fluorescein Diacetate(FDA), (d) β-glucosidase in soil samples were estimated under different residue retention (RR) and conventional tillage at the different depth 0-15 cm and 15-30 cm. The residue retentionswere no residue retention (0%), 30 percent residue retention and 90 percent residue retention. Each data point represents an average with an error bar as the standard error of three replicated observations.

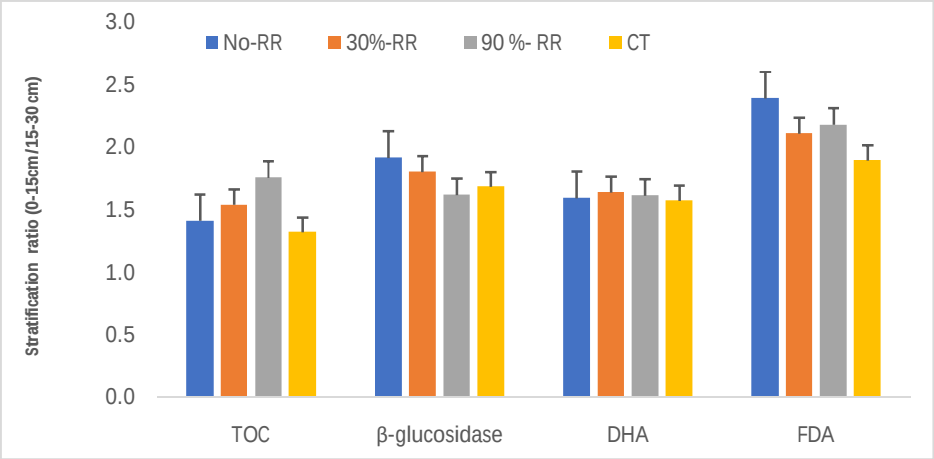

Figure 2. Stratification ratio (0-15 cm/15-30cm) forTOC and soil enzymatic activities DHA; β-glucosidase activity; FDA under residue retention (RR); 0 percent, 30 percent and 90 percent and CT. The vertical bar represents a standard error.

Table2.The correlation coefficient between biochemical (DHA, FDA and β-glucosidase) and chemical properties (TOC) in soil samples (n=40)

	TOC	DHA	FDA	β-glucosidase
TOC	-			
DHA	0.84**	-		
FDA	0.78*	0.94**	-	
β-glucosidase	0.78*	0.95**	0.92**	-

Correlation is significant at * p= 0.05 level, ** p=0.01 level

DISCUSSION

Climate-smart agricultural practices influence soil enzyme activities to varying degrees. Significant variations in enzyme activities were observed under different levels of crop residue retention (90%, 30%, 0%) compared to conventional tillage. Notable differences in SOC and enzyme activities were recorded in both surface and subsurface soils among the residue retention treatments. Our findings showed that SOC was significantly higher under 90 percent crop residue retention in the surface soil compared to CT.The significant increase in soil carbon over time could be due to several factors: (a) enhanced mineralization process of residues, and released more carbon, (b) a reduction in the loss of various soil organic carbon pools due to decreased carbon oxidation, and (c) the interaction between residues and clay complexes in black soil, which formed a highly labile carbon pool. In contrast, soils without residue showed limited microbial biomass which might have caused insufficient carbon and nitrogen availability. Soil organic carbon dynamics in terrestrial ecosystems are primarily influenced by the complex interactions between soil properties and agricultural management practices (Mohanty

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et al., 2020). Crop residues were the primary contributors to carbon fractions and their sequestration in the soil (Kukal & Bawa, 2014). Residue cover acts as a physical barrier against the impact of raindrops, helping to maintain soil moisture, reduce erosion (Kumar et al., 2018; Zhao et al., 2019), and lower carbon dioxide emissions (Busari et al., 2015), thereby preserving soil labile carbon.Kumar *et al.,*(2017), Hati *et al.,* (2015), and McCarty *et al.,* (1997), reported that conservation tillage, particularly no-till (NT), results in higher SOC concentrations in the topsoil and alters its distribution throughout the soil profile. The greatest differences in SOC concentration between tillage treatments were observed in the surface soils, in the order of RT > NT > CT. Several studies have shown that long-term conservation tillage systems (NT and RT) maintain higher SOC levels in surface soils compared to CT (Conant *et al*., 2007; Lopez-Fando*et al.,* 2009). The increased SOC concentrations are typically attributed to a variety of interacting factors, including minimal soil disturbance, enhanced residue retention and addition, reduced surface soil temperatures, improved soil moisture, and lower erosion risks (Ismail *et al*., 1994). Crop residues contribute to the SOC pool, and returning more crop residues to the soil is linked to higher SOC concentrations (Dolan *et al.,* 2006). SOC is one of the soil biological properties most influenced by tillage practices (Somasundaram *et al.*, 2014).

The DHA activity in 90 per cent, 30 per cent, and conventional tillage varied from 70.55 to 103.57 µg TPF g^{-1} day^{-1} in the surface layer. The residue retention in no-tillage systems had a significant effect on the DHA activity. A similar finding was reported by Parihar *et al.*, (2016), where surface soils under no-tillage (NT) practices showed significantly higher DHA (122.35 µg TPF g^{-1} day^{-1}) compared to CT (77.07 µg TPF g^{-1} day^{-1}). The decomposition of retained maize residues releases carbon, which can be available to soil microbes, leading to higher DHA activity in the surface soils under a maizechickpea cropping system. Kumar *et al.*, (2017) reported significantly higher DHA in soybean + pigeon pea rotations, followed by maize-gram systems.

Dehydrogenase activity is a well-established indicator of biological activity in soils, as the enzyme exists as an integral part of microbial cells but does not accumulate extracellularly. The oxidation of soil organic matter by dehydrogenase involves the transfer of protons and electrons from substrates to acceptors and is considered to be linked to the respiration pathways of microorganisms (Das *et al.,* 2011). The DHA activity was significantly influenced by the availability of organic matter, soil temperature, and soil moisture. This is in conformity with the findings of Madejon*et al.,* (2007) and Tao *et al.,* (2009), who observed higher DHA activity under conservation agriculture systems with legume rotations compared to CT.

The mean FDA activity values for 90 per cent, 30 per cent, 0 per cent, and conventional tillage ranged from 22.91 to 30.85 µg fluorescein g^{-1} h^{-1} in both the surface and subsurface layers. It is noted that residue retention management practices had a significant effect on the surface layer during the cropping cycle. Similar findings were reported by Perez-Brandan *et al.,* (2012) and Gajda *et al.,* (2013), who observed higher soil microbial enzymatic activities under conservation agriculture with legume rotations compared to conventional tillage. A significant influence of SOM on various biological properties of soil has been documented (Askari *et al.,* 2014; Sinha *et al.,* 2014; Sinha NK, 2014; Marinari *et al.,* 2006). In this study, SOM concentration significantly influenced the TOC, DHA, FDA, and β-glucosidase activities, as supported by the strong correlations between soil biological properties and SOM content.

The higher β-glucosidase activity was observed in surface soils compared to subsurface soils in the maize-chickpea cropping system, which could likely be due to the increased carbon input from the fibrous root mass of maize in the previous year. This finding is consistent with the higher soil carbon concentration under 90 per cent residue retention compared to conventional tillage, and the significant positive correlations observed between β-glucosidase activity, residue load, and total organic carbon. Martin-Lammerding *et al.,* (2015) and Acar *et al.,* (2018) noted that β-glucosidase activity was highest under no-tillage (NT), followed by reduced tillage (RT), with CT showing the lowest levels of β-

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glucosidase activity. In addition, Jat *et al.,* (2021) and Acar *et al.*, (2018) also reported that β-glucosidase activity was significantly higher in rhizospheric soils compared to bulk soils.

CONCLUSION

The soil biological parameters ofthe Vertisols of central India under the maize-chickpea cropping system were significantly impacted by varying levels of crop residue retention management. The results clearly demonstrated that higher residue retention, particularly 90 per cent and 30 per cent, supported greater biological activity compared to conventional tillage. Residue retention, as a key component of conservation tillage, triggered a rapid response in soil microbial activity. Biological activities in the soil were predominantly concentrated in the upper layer (0–15 cm), where TOC, DHA, FDA, and β-glucosidase activities were notably higher. This increase could be attributed to the accumulation of SOM from crop residues, litterfall, root biomass, and root and soil biota exudates, as well as the enhanced interaction between the soil surface and atmospheric conditions, fostering soil biodiversity. The strong correlations observed between TOC and enzymatic activities (DHA, FDA, and β-glucosidase) in the surface layer highlight the critical role of organic carbon in promoting microbial activity and sustaining soil biodiversity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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