



RESEARCH ARTICLE

Effect of tillage and weed control approaches on soil biological health and rice crop performance under conservation agriculture

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Abstract

Conservation agriculture, a climate-resilient approach, improves holistic soil health but is often constrained by severe weed challenges. To assess the effect of tillage and weed management practices on soil biological health, a field experiment was conducted during the kharif seasons of 2019 and 2020 at the Research cum Instructional Farm, Indira Gandhi Krishi Vishwavidyalaya, Raipur (Chhattisgarh). The experiment with the rice variety “IGKV R1” was laid out in a split-plot design with five tillage practices as main plots, namely two conventional transplanted rice [CT(TPR)], one conventional direct-seeded rice [CT(DSR)], zero tillage (ZT) and zero tillage with residue retention (ZT+R) and three weed management practices as sub-plots, replicated thrice. The results revealed that the conventional transplanted system [CT(TPR)] recorded the highest economic yield, which was of 7.66 % higher than that of ZT+R. Soil biological properties, including dehydrogenase activity (DHA), fluorescein diacetate (FDA) and bacterial, fungal and actinomycete populations, showed significant variation across the observation stages. These parameters increased after herbicide application and declined towards harvest. Among the tillage practices, ZT+R recorded the highest soil biological activity, whereas CT(TPR) recorded the lowest, indicating greater sustainability under conservation agriculture. Among weed management practices, integrated weed management (IWM) i.e. oxadiargyl 80 g ha⁻¹ pre-emergence (PE) followed by hand weeding at 25 days after sowing (DAS)/T resulted in superior performance across all parameters and produced 47 % higher grain yield than the weedy check. Therefore, the combined adoption of ZT+R and IWM is socio-ecologically acceptable and recommended for sustainable rice production.

Keywords: conservation tillage; conventional tillage; integrated weed management; soil biological health and yield

Introduction

Rice stands as a vital staple food, crucial for nourishing over half of the world's population, particularly in Asia. India ranks second in rice consumption, accounting for 108.5 million metric tons, trailing behind China (1). Conventional rice cultivation, which involves puddling to maintain a shallow water layer post-transplantation and suppress weeds, has drawbacks. It is water-, capital- and energy-intensive, leading to soil structure degradation (2). Transplanting requires substantial labor (300–350 hr ha⁻¹) and causes subsurface compaction in certain soil types (3). Tillage enhances soil moisture retention, weed and pest control and the incorporation of fertilisers and organic matter (4). However, excessive tillage oxidises soil organic matter, breaks down soil aggregates and triggers erosion (5). The burning of crop residues and fossil fuels contributes to greenhouse gas emissions, soil health decline, increased production costs and reduced farmer income (6). Hence, adopting summer legumes under reduced tillage and residue incorporation can enhance productivity, soil

carbon and energy savings (7), thereby promoting conservation agriculture.

Conservation agriculture, which integrates practices to enhance soil health, fertility and structure while mitigating soil degradation, improving water infiltration, reducing pesticide use and sequestering carbon, is gaining momentum globally. Currently practiced on nearly 160 million hectares worldwide, it covers a diverse range of climates and production systems (8). However, its adoption in India remains limited, with only 1.5 million hectares under zero-till wheat in Northwestern India (9). Conventional tillage, by disrupting the soil and exposing organic matter to rapid decomposition, tends to reduce long-term microbial habitat quality and soil enzyme activity. It may increase short-term mineralisation but lowers sustained biological function (10, 11). Conversely, reduced tillage or no-till practices can increase microbial biomass and improve soil biological health due to greater retention of organic matter and less disturbance of soil communities (12).

However, weed infestation is the main constraint in conservation agriculture and herbicides are a potent solution for weed management. Field and laboratory studies have shown that common rice herbicides may alter soil enzyme activities (dehydrogenase, etc) shortly after application; in some cases, low doses stimulate certain enzyme activities, whereas higher or double doses inhibit them (13). Recommended field doses often produce smaller or transient shifts in microbial community composition, but these changes are measurable (14). Some herbicides affect redox-sensitive reactions in submerged (paddy) soils and can influence Fe and Mn availability as well as nutrient transformation rates, which in turn affect plant uptake and microbial nutrient cycling (13, 14). Many studies have reported partial recovery of microbial populations and functions within weeks to months; however, persistent residues or repeated applications can prolong these impacts. The risk is context-dependent, as soil texture, organic matter, flooding regime and herbicide chemistry all modify the outcomes (14). Challenges such as herbicide resistance and the adverse effects of persistent soil herbicides pose significant constraints to conservation agriculture, necessitating integrated weed management strategies aligned with its principles (15).

Materials and Methods

Details of experimental site

The present investigation was conducted in kharif seasons in 2019 and 2020 at the Research cum Instruction Farm, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India. The site is located at a latitude of 21.2376° N, a longitude of 81.7055° E and an altitude of 290.20 m above mean sea level, where adequate irrigation and drainage facilities exist. The soil in the experimental field was silty clay in texture. It was neutral in reaction (pH 6.86) with normal electrical conductivity (0.349 dS m⁻¹). The soil had low nitrogen, medium phosphorus and high potassium contents. At the initiation of the experiment, the soil was silty clay (vertisol) comprising 19.09 % sand, 31.23 % silt and 49.68 % clay, with a pH of 6.83, EC of 0.348 dS m⁻¹, 0.43 % organic carbon, 223.54 kg N ha⁻¹ available nitrogen, 17.56 kg P₂O₅ ha⁻¹ available phosphorus and 320.13 kg K₂O ha⁻¹ available potassium.

Climate of the experimental site

Raipur falls under the Chhattisgarh plains agro-climatic sub-zone and has a dry-moist to sub-humid climatic condition. The region receives an average annual rainfall of 1250 mm, of which about 87 % is received during the rainy season (June–September) and the rest 13 % during the winter season (October–February). The crop was sown on 7 July 2019 and harvested on 17 November 2019 during the first year, while in the second year it was sown on 1 July 2020 and harvested on 4 November 2020. The meteorological data recorded during the experimental period showed that the crop received 1055 mm and 782.4 mm of rainfall

during the crop period in 2019 and 2020 respectively. The maximum temperature during the crop period varied from 28.00 to 35.50 °C in 2019 and from 29.1 to 33.40 °C in 2020, while the minimum temperature varied from 15.15 to 26.40°C and from 12.17 to 26.10 °C in 2019 and 2020 respectively. The maximum relative humidity throughout the crop season varied between 82.00 % and 94.00 % in 2019 and between 82.00 % and 92.00 % in 2020, whereas the minimum relative humidity varied from 38.00 to 87.43 % and from 38.00 to 86.11 % in 2019 and 2020 respectively. The average wind velocity for different weeks varied from 1.20 to 10.90 kmph, 2.10 to 10.40 kmph in 2019 and 2020 respectively.

Experimental design and treatment details

The experiment was laid out in a split-plot design with five tillage practices as main plots and three weed management practices as sub-plots replicated thrice. A rice-wheat-cowpea (fodder) cropping system in the respective three seasons of kharif, rabi and summer was adopted to validate conservation agriculture principles. The treatments applied to rice were as follows: i.e., the first season treatment of conventional transplanted rice [CT(TPR)]-CT-CT, CT (TPR)-zero tillage (ZT)-ZT, conventional direct-seeded rice [CT(DSR)]-CT-ZT and two ZT-zero tillage with residue retention (ZT+R)-ZT and ZT+R-ZT+R-ZT+R in main plots (Table 1). In the subplots, the weed management treatments comprised recommended herbicides [pyrazosulfuron 20 g ha⁻¹ pre-emergence (PE) followed by (*fb*) penoxsulam 22.5 g ha⁻¹ post-emergence (PoE)], IWM [oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 days after transplanting/sowing (DAT/S)] and a weedy check.

Crop management

The test variety used was “*IGKVRI*” sown as per the treatments with the recommended dose of fertilisers. Sowing of the crop was done on 7th of July, 2019 and harvested on 17th November, 2019 in the first year and in the second year, sowing was done on 1st July, 2020 and the crop was harvested on 4th November, 2020. The required number of herbicides (200 g ha⁻¹ of pyrazosulfuron, 104 mL ha⁻¹ of penoxsulam and 100 g ha⁻¹ of oxadiargyl) were sprayed using 375 L ha⁻¹ of water with a calibrated knapsack sprayer (make: standard agricultural model, 15 L capacity) fitted with a flat-fan nozzle, ensuring uniform spray distribution. Calibration was performed prior to application to maintain a consistent spray volume as per recommended agronomic practices. Applications were carried out under favourable environmental conditions (low wind speed, moderate temperature and absence of rainfall) to ensure effective herbicide performance and minimise drift losses. Grain yield (t ha⁻¹) was recorded after harvesting and was expressed at 14 % moisture content. Data was analysed using analysis of variance (SAS Software packages, SAS EG 4.3). Assumptions of normality and homogeneity of variance were considered and treatment means were compared based on the critical difference (CD) test at $p < 0.05$ probability level.

Table 1. Brief information of the treatments used in kharif rice

Tillage and residue management (main plot)			Weed management (sub plot)
T ₁	CT (transplanted)	W ₁	Rec. herbicides (pyrazosulfuron 20 g ha ⁻¹ PE <i>fb</i> penoxsulam 22.5 g ha ⁻¹ PoE)
T ₂	CT (transplanted)	W ₂	IWM (oxadiargyl 80 g ha ⁻¹ PE <i>fb</i> hand weeding at 25 DAT/S)
T ₃	CT (direct seeded)	W ₃	Weedy check
T ₄	ZT (direct seeded)		
T ₅	ZT (direct seeded) + residue		

CT: conventional tillage; ZT: zero tillage; DAT/S: days after transplanting/sowing; HW: hand weeding; Rec. herbicides: recommended herbicides; PE: pre-emergence; PoE: post-emergence; *fb*: followed by; IWM: integrated weed management.

Observations and calculation

Soil biological properties studies

Sampling: Soil samples were collected diagonally from each plot before herbicide application (BA), 15 days after herbicide application (DAA) and at harvest for laboratory analysis of soil enzymatic activity, including dehydrogenase activity (DHA), fluorescein diacetate (FDA) hydrolase activity and soil microbial population estimation. The 15 DAA values were recorded by sampling soil exactly 15 days after the PoE herbicide spray timing in the chemical treatments. In the weedy check and IWM plots, which did not receive PoE herbicide, sampling was carried out on the same calendar date corresponding to 15 DAA of the sprayed plots to enable direct comparison at equivalent crop phenological stages.

Dehydrogenase activity: Dehydrogenase activity was determined by the reduction of triphenyl tetrazolium chloride (TTC) (16). Each soil sample (3 g) was treated with 0.1 g CaCO₃ and 1 mL aqueous 0.18 M TTC and incubated for 24 hr at 37 °C. Triphenyl formazan (TPF) was extracted from the reaction mixture (pH 5.3–5.6) using methanol and assayed at 485 nm. Dehydrogenase activity was expressed as milligrams of TPF formed g⁻¹ of dry soil hr⁻¹.

Fluorescein diacetate hydrolase activity: Fluorescein diacetate hydrolase activity was measured by the potassium phosphate buffer method followed by addition of chloroform/methanol (2:1 v/v) as described in previous study (17). Soil samples (2 g) were treated with 15 mL of 60 mM potassium phosphate buffer (pH 7.6) and 0.2 mL of 1000 µg FDA. After shaking for 20 min at 30 °C, 15 mL of chloroform/methanol (2:1 v/v) was added and centrifuged at 2000 rpm for 3 min. Fluorescein diacetate hydrolase activity was assayed at 490 nm and expressed as µg fluorescein g⁻¹ of dry soil hr⁻¹.

Population counts of soil total bacteria, fungi and actinomycetes: Microbial population analysis of the soil was performed using the serial dilution method followed by the pour plate technique. Soil samples were serially diluted and plated on nutrient agar, potato dextrose agar and Knight's agar media for total heterotrophic bacteria, fungi and actinomycetes, respectively. Microbial population was calculated based on per gram of dry soil using the following formula (18). The

operation of making serial dilutions, setting of agar plates and inoculation with appropriate media, was done in a sterilised atmosphere of laminar airflow chamber.

Population count of bacteria/actinomycetes/fungi

$$= \frac{\text{No. of CFU} \times \text{Dilution}}{\text{Dry weight of 1 g moist soil} \times \text{aliquot taken}}$$

Crop study

Sterility percentage: The number of filled and unfilled grains per panicle was counted separately from the five panicles in each plot and sterility percentage was computed using the following formula:

$$\text{Sterility percentage} = \frac{\text{Number of unfilled grains panicle}^{-1}}{\text{Total number of grains panicle}^{-1}} \times 100$$

Harvest index: The harvest index was computed using the following formula:

$$\text{Harvest index (\%)} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

Where,

Economic yield = Seed yield

Biological yield = Seed yield + Straw yield

Results

Soil biological properties

Soil enzyme studies

Dehydrogenase activity (mg TPF g⁻¹ of dry soil hr⁻¹): The data regarding DHA as influenced by different treatments are presented in Table 2. Among the tillage practices, ZT+R-ZT+R recorded

Table 2. Dehydrogenase activity in soil of rice is influenced by tillage and weed management practices under conservation agriculture (pooled data of years 2019 and 2020)

Treatments	Dehydrogenase activity (mg TPF g ⁻¹ of dry soil hr ⁻¹)				
	Pre-emergence herbicides		Post-emergence herbicide		
	BA	15 DAA	BA	15 DAA	At harvest
Tillage practices					
CT(TPR)-CT-CT	50.9	54.75	58.91	63.85	52.36
CT(TPR)-ZT-ZT	51.94	56.37	60.50	65.90	53.28
CT(DSR)-CT-ZT	51.18	57.98	61.99	67.32	55.37
ZT-ZT+R-ZT	57.27	63.22	68.09	73.49	65.19
ZT+R-ZT+R-ZT+R	63.19	86.91	95.44	98.40	71.76
SEm±	0.06	0.08	0.09	0.36	0.3
CD (p = 0.05)	0.21	0.25	0.28	1.18	0.97
Weed management					
Rec. herbicides	56.58	66.07	70.62	77.02	61.90
IWM	56.01	65.55	71.20	73.82	59.93
Weedy check	52.10	59.93	65.13	70.53	56.95
SEm±	0.09	0.11	0.12	0.49	0.4
CD (p = 0.05)	0.15	0.13	0.26	1.31	0.82
Interaction (T × W)	NS	NS	NS	NS	NS

CT(TPR): conventional transplanted rice; CT(DSR): conventional direct-seeded rice; ZT: zero tillage; ZT+R: zero tillage with residues; BA: before application of herbicides; DAA: days after application of herbicides; Rec. herbicides: recommended herbicides; IWM: integrated weed management; SEm: standard error of the mean; CD: critical difference.

the highest DHA, with a peak value of 98.40 mg TPF g⁻¹ soil hr⁻¹ at 15 DAA of PoE herbicide, whereas CT(TPR)-CT-CT recorded the lowest value. The increase under ZT+R-ZT+R-ZT+R was about 54 % higher than that under CT(TPR)-CT-CT at peak stage.

Among weed management practices, the recommended herbicide sequence (pyrazosulfuron-ethyl 20 g ha⁻¹ PE *fb* penoxsulam 22.5 g ha⁻¹ PoE) recorded slightly higher DHA than integrated weed management (oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T), with peak values of 77.02 and 73.82 mg TPF g⁻¹ soil hr⁻¹, respectively, at 15 DAA of the PoE herbicide, representing an increase of about 1–4 % over IWM. The weedy check recorded lower DHA, with a peak value of 70.53 mg TPF g⁻¹ soil hr⁻¹ at the same stage, which was about 8–10 % lower than the recommended herbicide sequence and 4–5 % lower than integrated weed management. Dehydrogenase activity increased after herbicide application, reached a maximum at 15 DAA of PoE herbicide and declined towards harvest. The interaction effect between tillage and weed management was non-significant.

Fluorescein diacetate hydrolase activity (µg fluorescein g⁻¹ of dry soil hr⁻¹): Fluorescein diacetate hydrolase activity was significantly influenced by tillage and weed management practices at all observation stages (Table 3). Among the tillage practices, ZT+R-ZT+R-ZT+R recorded the highest FDA activity, with a peak value of 55.93 µg fluorescein g⁻¹ soil hr⁻¹ at 15 DAA of the PoE herbicide, whereas CT(TPR)-CT-CT recorded the lowest value. The increase under ZT+R-ZT+R-ZT+R was about 54–62 % higher than that CT (TPR)-CT-CT.

Among the weed management practices, the recommended herbicide sequence (pyrazosulfuron-ethyl 20 g ha⁻¹ PE *fb* penoxsulam 22.5 g ha⁻¹ PoE) recorded slightly higher FDA activity than integrated weed management (oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T), with peak values of 43.67 and 41.92 µg fluorescein g⁻¹ soil hr⁻¹, respectively at 15 DAA of the PoE herbicide, representing an increase of about 3–4 % over IWM. The weedy check recorded lower FDA activity, with a peak value of 40.14 µg fluorescein g⁻¹ soil hr⁻¹, which was about 7–8 % lower than the recommended herbicide sequence and 3–4 % lower than integrated weed management. Fluorescein diacetate hydrolase

activity increased after herbicide application, peaked at 15 DAA of the PoE herbicide and declined at harvest. However, the interaction effect of tillage and weed management practices on FDA activity was non-significant at all observation stages.

Soil microbial population

Bacteria population (× 10⁶ cfu g⁻¹ soil): Data regarding bacterial populations as influenced by different treatments are presented in Fig. 1a. The bacterial population differed significantly during all observation periods (i.e. BA, 15 DAA of both PE and PoE herbicides and at harvest). The population increased after herbicide application but declined to approximately the initial population at harvest. Among the tillage practices, ZT+R-ZT+R-ZT+R recorded the highest bacterial population, with a peak mean value of 49.25 × 10⁶ cfu g⁻¹ soil at 15 DAA of PoE herbicide, whereas CT(TPR)-CT-CT recorded the lowest (23.11 × 10⁶ cfu g⁻¹ soil). This represents an increase of about 113 % under ZT+R-ZT+R-ZT+R.

Among the weed management practices, IWM i.e. (oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T) recorded a higher bacterial population than the recommended herbicide treatment (pyrazosulfuron-ethyl 20 g ha⁻¹ PE *fb* penoxsulam 22.5 g ha⁻¹ PoE), with peak values of 32.17 and 23.87 × 10⁶ cfu g⁻¹ soil, respectively, at 15 DAA, indicating an increase of about 35 % under IWM. The weedy check recorded the highest bacterial population (39.93 × 10⁶ cfu g⁻¹ soil), which was about 67 % higher than that under the recommended herbicide treatment and 24 % higher than that under IWM. Bacterial population increased after herbicide application, reached a maximum at 15 DAA of PoE herbicide and declined towards harvest. The interaction effect was non-significant.

Fungi population (× 10³ cfu g⁻¹ soil): Data regarding fungi population as influenced by different treatments are presented in Fig. 1b. The fungi population differed significantly during all observation periods (i.e., BA, 15 DAA of both PE and PoE herbicides and at harvest) increasing after herbicide application but declining to about the initial population at harvest. ZT+R-ZT+R-ZT+R recorded the highest fungal population, with a peak mean value of 44.91 × 10³ cfu g⁻¹ soil at 15 DAA, whereas CT(TPR)-CT-CT recorded the lowest (20.73 × 10³ cfu g⁻¹ soil), showing an increase of about 117 %.

Table 3. Fluorescein dehydrogenase activity in soil of rice is influenced by tillage and weed management practices under conservation agriculture (pooled data of years 2019 and 2020)

Treatments	Fluorescein dehydrogenase activity (FDA) (µg fluorescein g ⁻¹ of dry soil hr ⁻¹)				
	Pre-emergence herbicides		Post-emergence herbicide		
	BA	15 DAA	BA	15 DAA	At harvest
Tillage practices					
CT(TPR)-CT-CT	31.08	31.54	33.40	36.24	32.56
CT(TPR)-ZT-ZT	31.52	32.53	34.51	37.41	33.02
CT(DSR)-CT-ZT	31.68	33.04	34.99	38.27	33.63
ZT-ZT+R-ZT	34.71	36.39	38.57	41.69	37.09
ZT+R-ZT+R-ZT+R	45.49	50.16	54.22	55.93	48.19
SEm±	0.03	0.03	0.05	0.26	0.16
CD (p = 0.05)	0.10	0.09	0.17	0.86	0.53
Weed management					
Rec. herbicides	35.80	37.75	40.02	43.67	38.19
IWM	35.61	37.57	40.37	41.92	37.10
Weedy check	33.27	34.87	37.03	40.14	35.41
SEm±	0.04	0.04	0.07	0.36	0.22
CD (p = 0.05)	0.12	0.11	0.21	1.05	0.65
Interaction (T × W)	NS	NS	NS	NS	NS

CT(TPR): conventional transplanted rice; CT(DSR): conventional direct-seeded rice; ZT: zero tillage; ZT+R: zero tillage with residues; BA: before application of herbicides; DAA: days after application of herbicides; Rec. herbicides: recommended herbicides; IWM: integrated weed management; SEm: standard error of the mean; CD: critical difference.

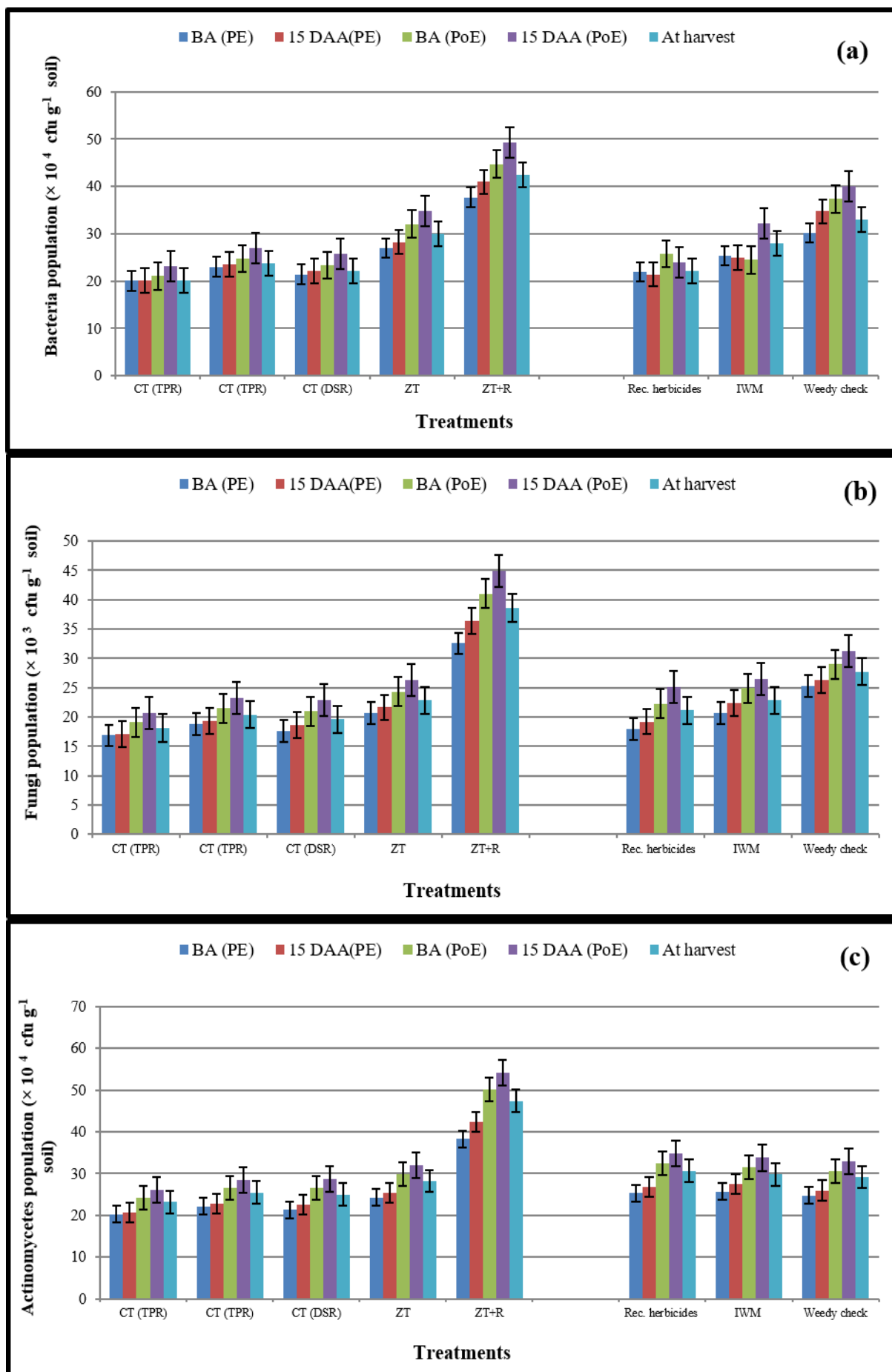


Fig. 1. Soil microbial population in rice as influenced by tillage and weed management practices under conservation agriculture (pooled data of 2019 and 2020). a: bacteria; b: fungi; c: actinomycetes. BA: before application of herbicide; DAA: days after application of herbicide; CT(TPR): conventional transplanted rice; CT(DSR): conventional direct-seeded rice; ZT: zero tillage; ZT+R: zero tillage with residues. Rec. herbicides: pyrazosulfuron 20 g ha⁻¹ followed by penoxsulam 22.5 g ha⁻¹ PoE; IWM: oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 days after transplanting/sowing (DAT/S).

Among weed management practices, IWM i.e. oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T, recorded slightly higher fungal population than pyrazosulfuron-ethyl 20 g ha⁻¹PE *fb* penoxsulam 22.5 g ha⁻¹PoE, with peak values of 26.52 and 25.08 × 10³ cfu g⁻¹ soil, respectively representing an increase of about 5–6 % under IWM. The weedy check recorded the highest fungal population (31.20 × 10³ cfu g⁻¹ soil), which was about 24 % higher than the recommended herbicide sequence and 18 % higher than IWM. However, the interaction effect of tillage and weed management practices on fungal population was non-significant at all observation periods.

Actinomycetes population (× 10⁴ cfu g⁻¹ soil): The data regarding the actinomycetes population as influenced by different treatments are presented in Fig. 1c. Actinomycetes population was significantly different in all observation periods (i.e. BA, 15 DAA of both PE and PoE herbicides and at harvest) increasing after herbicide application but declining to about the initial population at harvest. Among the tillage practices, ZT+R-ZT+R-ZT+R recorded the highest actinomycetes population, with a peak mean value of 54.18 × 10⁴ cfu g⁻¹ soil at 15 DAA of the PoE herbicide, whereas CT(TPR)-CT-CT recorded the lowest (26.01 × 10⁴ cfu g⁻¹ soil), indicating an increase of about 108 %.

Among the weed management practices, pyrazosulfuron-ethyl 20 g ha⁻¹PE *fb* penoxsulam 22.5 g ha⁻¹PoE recorded slightly higher actinomycetes population than oxadiargyl 80 g ha⁻¹PE *fb* hand weeding at 25 DAS/T i.e. IWM, with peak values of 34.83 and 33.75 × 10⁴ cfu g⁻¹ soil, respectively, representing an increase of about 3 %. The weedy check recorded lower actinomycetes population (32.90 × 10⁴ cfu g⁻¹ soil) compared to the recommended herbicide sequence (~6 % lower) and IWM (~3 % lower). The interaction effect on actinomycetes population due to tillage and weed management practices was non-significant at all observation periods.

Crop parameters

Dry matter accumulation (g m⁻²): The data presented in Table 4 revealed that dry matter accumulation in plants was significantly different at all observations. Dry matter accumulation in plants in all plots gradually increased as

growth advanced. Among tillage practices, CT(TPR)-CT-CT produced significantly higher plant dry matter at all observations; however, it was statistically at par with CT(TPR)-ZT-ZT, whereas the lowest was recorded under CT(DSR)-CT-ZT at all observation periods.

It was observed that significantly higher plant dry matter accumulation was recorded at all observation periods when the crop was treated with IWM i.e. oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T, compared to the other two treatments, while the lowest dry matter accumulation was observed in the weedy check. However, the interaction effect on dry matter accumulation due to tillage and weed management practices was non-significant at all observation periods.

Grain yield (t ha⁻¹) and yield attributing characters: The data with respect to these parameters are presented in Table 4. Filled grains per panicle were significantly different among all treatments in both tillage and weed management practices. Sterility percentages (%) were significantly different among all treatments. Among the tillage practices, CT(TPR)-CT-CT, being statistically at par with CT(TPR)-ZT-ZT, produced a significantly lower sterility percentage (%) compared to the other tillage practices, whereas the highest was recorded under CT(DSR)-CT-ZT. Significantly lower sterility percentage (%) was also noticed when the crop was treated with IWM i.e. oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T, compared to the other two treatments, while the highest sterility percentage (%) was observed in the weedy check. Grain yield ha⁻¹ was significantly different among all treatments. Among the tillage practices, CT(TPR)-CT-CT, being statistically at par with CT(TPR)-ZT-ZT, produced a significantly higher grain yield compared to the other tillage practices, whereas the lowest yield was recorded under CT(DSR)-CT-ZT. As regards the influence of weed management practices, the significantly higher grain yield was observed when the crop was treated with IWM i.e. oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T over the other two treatments. The lowest grain yield was observed in the weedy check.

The harvest index did not differ significantly among the tillage and weed management practices. As regards the influence of

Table 4. Dry matter accumulation, no. of filled grains per panicle, sterility percentage, grain yield of rice as influenced by tillage and weed management practices under conservation agriculture (pooled data of years 2019 and 2020)

	Dry matter accumulation (g m ⁻²)		No. of filled grains panicle ⁻¹	Sterility percentage	Grain yield (t ha ⁻¹)	Harvest index (%)
Tillage practices	60 DAS/T	At harvest				
CT(TPR)-CT-CT	445.77	1204.25	141.99	12.05	5.61	43.56
CT(TPR)-ZT-ZT	428.52	1169.2	135.95	12.50	5.45	44.43
CT(DSR)-CT-ZT	295.56	942.77	107.63	16.58	4.57	44.20
ZT-ZT+R-ZT	323.13	1038.59	124.74	13.95	5.10	44.18
ZT+R-ZT+R-ZT+R	333.7	1054.91	127.65	13.21	5.18	41.54
SEm±	10.34	29.88	3.90	0.51	0.08	1.16
CD (p = 0.05)	33.73	97.43	12.73	1.68	0.27	NS
Weed management						
Rec. herbicides	409.66	1210.05	141.45	12.74	5.79	43.34
IWM	450.62	1328.38	160.79	10.75	6.35	45.34
Weedy check	235.73	707.4	80.54	17.48	3.41	42.06
SEm±	13.61	39.31	1.31	0.40	0.11	1.30
CD (p = 0.05)	40.14	116.00	3.87	1.19	0.34	NS
Interaction (T × W)	NS	NS	NS	NS	S	NS

CT(TPR): conventional transplanted rice; CT(DSR): conventional direct-seeded rice; ZT: zero tillage; ZT+R: zero tillage with residues; DAS/T: days after sowing/transplanting; Rec. herbicides: recommended herbicides; IWM: integrated weed management; SEm: standard error of the mean; CD: critical difference.

weed management practices, it was observed that a higher harvest index was noticed when the crop was treated with IWM i.e. oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T.

Discussion

Effect of tillage and weed management practices on soil enzymatic activity

Tillage practices had a marked effect on soil enzymatic activities, including DHA and FDA hydrolase, across all observation periods (BA, 15 DAA of pre- and PoE herbicides and at harvest). ZT+R-ZT+R-ZT+R recorded significantly higher DHA and FDA activities than the other tillage treatments, while CT(TPR)-CT-CT showed the lowest values at every sampling stage (19, 20). The enhanced enzymatic activities under ZT+R were mainly due to increased organic carbon inputs from surface-applied residues, better soil aggregation, improved moisture retention and protection of extracellular enzymes from rapid degradation. In contrast, intensive puddling and repeated tillage in the conventional system accelerated organic matter oxidation and limited substrate availability, resulting in suppressed enzyme activities (21).

Weed management practices significantly influenced soil enzymatic activities. The recommended herbicide sequence (pyrazosulfuron-ethyl 20 g ha⁻¹ PE *fb* penoxsulam 22.5 g ha⁻¹ PoE) recorded the highest DHA and FDA activities across most observation periods, followed by IWM treatment (oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T), while the weedy check produced the lowest values. Enzymatic activities increased after herbicide application in all treatments, peaking around 15 DAA before declining towards harvest. The superior performance of the recommended herbicide sequence is attributed to a transient stimulatory effect at field-recommended doses. Acetolactate synthase (ALS)-inhibiting herbicides such as pyrazosulfuron-ethyl and penoxsulam can promote DHA and FDA activities by selectively enhancing the growth and metabolic activity of microbial groups capable of degrading these compounds or utilising their early breakdown products as additional carbon and energy sources (22, 23). Although IWM provided effective weed control with minimal chemical input and avoided prolonged toxicity, it did not produce the same level of enzymatic stimulation observed with the ALS-inhibitor sequence (22, 24). The weedy check exhibited the lowest enzymatic activities due to intense crop-weed competition, which reduced root exudation and the availability of readily accessible organic substrates essential for microbial enzyme production (25).

The interaction effect between tillage and weed management practices was non-significant for both DHA and FDA activities at all observation periods. However, the combination of ZT+R with the recommended herbicide sequence consistently supported the highest enzymatic activities. These findings suggest that conservation agriculture practices (ZT+R) integrated with the timely application of pyrazosulfuron-ethyl followed by penoxsulam can enhance soil enzymatic functioning through increased carbon inputs and transient microbial stimulation, thereby contributing to improved nutrient cycling and long-term soil biological health in rice-based systems (19, 20, 26). Such dose-dependent stimulation of soil enzymes at recommended field rates of ALS inhibitors is commonly reported and is generally considered safe for soil health when used judiciously (22, 27).

Effect of tillage and weed management practices on soil microbial population

Tillage practices significantly influenced the population of soil bacteria ($\times 10^6$ cfu g⁻¹ soil), fungi ($\times 10^3$ cfu g⁻¹ soil) and actinomycetes ($\times 10^4$ cfu g⁻¹ soil) across all observation periods (BA, 15 DAA of pre- and PoE herbicides and at harvest). ZT+R-ZT+R-ZT+R recorded significantly higher populations of bacteria, fungi and actinomycetes than all other tillage treatments, while CT(TPR)-CT-CT registered the lowest counts at every sampling stage (28, 29). These improvements under ZT+R resulted from greater surface retention of crop residues, which supplied continuous labile carbon substrates, enhanced soil aggregation, improved moisture conservation and minimized physical disruption of microbial habitats. Intensive puddling and repeated tillage in CT(TPR)-CT-CT promoted rapid oxidation of organic matter, breakdown of soil aggregates and reduced substrate availability, thereby limiting microbial proliferation (30).

Weed management practices also significantly affected soil microbial populations. The higher bacterial and fungal populations under IWM (oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 DAS/T), compared to the recommended herbicide sequence (pyrazosulfuron-ethyl 20 g ha⁻¹ PE *fb* penoxsulam 22.5 g ha⁻¹ PoE) may be attributed to reduced chemical stress and improved soil conditions resulting from partial reliance on cultural practices. The integration of manual weeding likely enhanced soil aeration and organic matter inputs, thereby promoting microbial growth (31, 32).

The highest bacterial and fungal populations recorded under weedy check can be explained by continuous rhizodeposition and greater plant diversity, which supply readily available carbon substrates and create a favourable microenvironment for microbial proliferation. Increased root exudation and heterogeneous organic inputs under diverse vegetation are known to stimulate microbial abundance, particularly fast-growing bacteria and fungi (33, 34). In contrast, actinomycetes population was slightly higher under the recommended herbicide sequence and comparatively lower under weedy check. This may be due to reduced competition from bacteria in herbicide-treated plots and the ability of actinomycetes to utilise more complex carbon substrates. Under weedy conditions, abundant labile carbon favours rapid bacterial growth, leading to competitive suppression of actinomycetes (35, 36). Overall, the differential response of microbial groups indicates that while weed presence enhances total microbial abundance through increased carbon inputs, it may alter microbial community composition by favouring bacteria and fungi over actinomycetes.

The interaction effect between tillage and weed management was non-significant for microbial populations at all observation periods. However, the combination of ZT+R with the recommended herbicide sequence consistently supported the most favourable soil biological environment. These results demonstrate that conservation agriculture (ZT+R), integrated with timely application of pyrazosulfuron-ethyl followed by penoxsulam, can enhance microbial habitat quality and support higher microbial populations through increased organic inputs and selective stimulation of degradative microbial communities (29, 37). Such transient stimulation following herbicide application is commonly reported when microbes metabolise herbicide molecules, although the magnitude depends on herbicide chemistry, dose, soil type and environmental conditions (38, 39).

Crop parameters

The variation in plant dry matter accumulation among different tillage practices might be attributed to the favourable microclimate created for crop growth and development, resulting in reduced competition for growth resources (40). Throughout the crop growth period, the control plot (weedy check) showed the lowest dry matter accumulation which might have resulted from severe crop-weed competition. The increase in foliage in the best treatments might have enhanced photosynthesis, resulting in the highest plant dry matter accumulation over the other treatments (41).

A higher number of filled grains panicle⁻¹ might be attributed to increased photosynthesis and greater translocation of photosynthates from the source to the sink (41, 42). Consequently, spikelet sterility is negatively related to the crop grain yield development of plants (42, 43). Higher rice yield and yield-attributing characters under CT treatments during the initial years might be due to the favourable effect of tillage practices on accelerating organic matter decomposition, higher nutrient availability and enhanced root growth (44). The increased yield in these treatments might be due to the cumulative effect of increased number of panicle bearing tillers per unit area, filled grains per panicle (45–48).

Advanced discussion

Linking soil biological activity with soil organic carbon and microbial biomass carbon

Although soil organic carbon (SOC) and microbial biomass carbon (MBC) were not directly measured in the present study, the observed trends in soil enzyme activities (DHA activity and FDA hydrolysis) and microbial populations strongly suggest a close association with these important soil quality indicators. SOC serves as the primary substrate and energy source for soil microorganisms, thereby regulating microbial biomass and enzymatic activity (19). Higher DHA and FDA values under ZT+R indicate enhanced microbial respiration and metabolic activity, which are typically associated with increased SOC levels in residue retention systems (20).

Residue retention in ZT+R likely contributed to greater carbon inputs, reduced oxidative losses and improved carbon stabilisation, thereby promoting microbial proliferation and activity. Similar findings have been reported in conservation agriculture systems, where SOC accumulation enhances soil biological functioning and nutrient cycling (21). Microbial biomass carbon (MBC), a sensitive indicator of soil biological health, is expected to be higher under ZT+R due to minimal soil disturbance and continuous supply of organic matter (26). The increased microbial populations observed in this study further support the likelihood of elevated MBC under conservation practices (49).

Mechanistic basis of enzyme activity (dehydrogenase activity, fluorescein diacetate activity and beyond)

Dehydrogenase activity reflects intracellular oxidative metabolism and is directly linked to viable microbial cells, whereas FDA hydrolysis represents overall microbial enzymatic activity, including contributions from lipases, proteases and esterases (25). The increase in DHA and FDA shortly after herbicide application may be attributed to the stimulation of specific microbial communities capable of degrading herbicide molecules and utilising them as carbon and energy sources (23). However, the subsequent decline toward harvest suggests that this stimulatory effect is transient and may be followed by substrate depletion or toxic effects on sensitive microbial groups (31).

In addition to DHA and FDA, other enzymes such as urease and phosphatase play critical roles in nitrogen and phosphorus cycling, respectively (27). The inclusion of these enzymes in future studies would provide a more comprehensive understanding of nutrient dynamics under different tillage and weed management practices. Urease activity is associated with nitrogen mineralisation, while phosphatase activity is linked to the transformation of organic phosphorus. Under conservation agriculture, increased residue retention and microbial biomass are expected to enhance these enzyme activities, thereby improving nutrient availability and soil fertility (27, 33).

Herbicide-microbe interactions and soil ecological implications

Herbicide application can exert both stimulatory and inhibitory effects on soil microorganisms, depending on concentration, persistence and environmental conditions (29). The observed short-term increase in microbial activity after herbicide application suggests selective enrichment of herbicide-tolerant or herbicide-degrading microbial populations that possess specific metabolic pathways for utilising these compounds as substrates (23). However, repeated or prolonged herbicide use may disrupt microbial diversity and functional stability, with potential negative consequences for long-term soil health. Residue retention under ZT+R likely mitigates these effects by buffering the soil environment, increasing organic matter content and supporting more diverse microbial communities (21, 34).

Soil biology-yield relationship

The relationship between soil biological activity and crop yield is complex and often non-linear (30). In the present study, CT(TPR) recorded higher yield despite lower biological activity, which may be attributed to greater immediate nutrient availability resulting from intensive tillage. In contrast, ZT+R demonstrated comparable yields with significantly higher biological activity, indicating its potential for sustainable productivity. Enhanced microbial activity improves nutrient cycling, soil structure and water retention, thereby contributing to long-term yield stability (30, 35).

System-level insights under conservation agriculture

At the system level, conservation agriculture integrates physical, chemical and biological processes to improve overall soil health. Minimal soil disturbance reduces carbon losses; residue retention increases organic matter inputs and enhanced microbial activity drives efficient nutrient cycling. The combined effects lead to improved soil structure, increased water infiltration and greater resilience to environmental stresses (19, 49). The present findings highlight that integrating ZT+R with IWM creates a balanced agroecosystem that simultaneously improves soil biological health and sustains crop productivity (21).

Limitations of the study

The present study provides valuable insights into the effects of tillage and weed management practices on soil biological properties and crop performance. However, certain limitations should be acknowledged. First, the experimental duration was relatively short, which may not fully capture the long-term impacts of conservation agriculture practices on soil health and sustainability. Long-term experiments are generally required to observe substantial changes in soil organic carbon dynamics and microbial community structure (19, 50).

Second, the data were pooled across years. Although this was justified by the minimal inter-annual variability observed during the initial phase of the experiment, it may limit the assessment of year-wise variability and temporal trends (51, 52). Third, while the study evaluated overall microbial activity and enzyme responses, the potential effects of herbicides on non-target soil organisms and microbial diversity were not examined in detail. Such effects may have important implications for the long-term ecological balance of the soil system (23, 49).

Finally, the findings are based on a specific agro-climatic region and experimental conditions, which may restrict their broader applicability. Therefore, caution should be exercised when extrapolating the results to other regions with different soil types, climates and management practices (50, 52). Future research should focus on long-term trials incorporating detailed analyses of microbial diversity (e.g. metagenomics) and multi-location validation to strengthen the generalisation of conservation agriculture practices.

Conclusion

The outcomes revealed that, among the tillage practices, the transplanted system of establishment, i.e. CT(TPR)-CT-CT, proved to be most beneficial in terms of dry matter accumulation, highest yield and yield attributing characters. However, ZT+R-ZT+R-ZT+R enhanced soil biological activities and produced only 7.66 % lower grain yield than CT(TPR)-CT-CT. Hence, in the long term, ZT+R-ZT+R-ZT+R may be considered a more eco-friendly and sustainable option. The recommended herbicide sequence (pyrazosulfuron-ethyl 20 g ha⁻¹ pre-emergence (PE) followed by penoxsulam post-emergence (PoE)) caused transient stimulation of soil biological parameters after application. However, this treatment resulted in comparatively poorer crop performance, with nearly 5 % lower grain yield than integrated weed management (IWM) i.e. oxadiargyl 80 g ha⁻¹ PE *fb* hand weeding at 25 days after sowing/transplanting (DAS/T) and was considered less sustainable due to its greater reliance on chemical herbicides. Moreover, IWM proved superior and registering significantly higher soil enzymatic activities and microbial populations and 47 % higher grain yield than the weedy check. These findings indicate that ZT+R combined with IWM offers a balanced, socio-ecologically sustainable option for rice production under conservation agriculture. Long-term studies are recommended to evaluate the cumulative effects of these practices on soil carbon sequestration, herbicide resistance development and system productivity across varying agro-climatic conditions.

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Authors' contributions

SM carried out the field research work, laboratory analyses, data interpretation and manuscript drafting. NT supervised the field work, reviewed the data and performed the critical review of the manuscript. MT, BSB, UKB and ID contributed to data review and

manuscript revision. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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