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HERBICIDE EFFICACY IN MAIZE (*ZEA MAYS* L.): EFFECTS OF TILLAGE AND WEED MANAGEMENT ON WEEDS, SOIL MICROBES AND PRODUCTIVITY

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ABSTRACT
A field experiment was conducted during rabi 2020-21 at the AICRP on Weed Management Block, Central Farm, Odisha University of Agriculture & Technology (OUAT), Bhubaneswar, Odisha, to evaluate the combined effects of tillage and weed-management practices on weed biomass, weed nutrient capture, culturable soil microbial populations and maize productivity. Three main-plot tillage practices, namely conventional tillage (CT), zero tillage with paddy-straw mulch @ 5 t ha^{-1} (ZT+M) and zero tillage by dibbling (ZT), were combined with four subplot weed-management practices: pendimethalin @ 1 kg ha^{-1} as pre-emergence, tembotrione @ 120 g ha^{-1} as post-emergence, manual weeding and weedy check. The experiment was laid out in a split-plot design with three replications, comprising 12 treatment combinations per replication and 36 experimental plots. Weed biomass was recorded at 30, 60 DAS and harvest, while culturable populations of bacteria, fungi and actinomycetes were enumerated at 7, 14 and 21 DAS using the serial dilution and spread-plate technique. Nutrient capture by weeds in terms of N, P and K was determined at different crop stages and maize grain and stover yields were recorded at harvest. Conventional tillage recorded the lowest weed biomass, whereas ZT resulted in greater weed biomass. Pendimethalin effectively restricted weed biomass and nutrient capture. ZT+M supported comparatively greater populations of bacteria, fungi and actinomycetes than CT and ZT. Maize grain yield was highest under CT and statistically comparable with ZT+M, while pendimethalin recorded the highest yield among weed-management treatments. The study demonstrates the importance of integrating tillage, residue retention and timely weed management to balance weed suppression, soil biological activity and maize productivity.

KEYWORDS: Conservation agriculture; Tillage; Weed management; Weed nutrient capture; Soil microbial population; Maize productivity.

INTRODUCTION
Maize (*Zea mays* L.) is an important cereal crop in resource-conserving production systems, where reduced soil disturbance and residue retention are used to improve soil functioning and reduce the operational costs associated with intensive tillage. However, the transition from conventional to conservation tillage can alter the distribution and emergence pattern of weed flora because weed seeds remain concentrated in the upper soil layer and soil disturbance is reduced. Consequently, successful conservation agriculture depends on weed management that maintains crop productivity without undermining soil biological functioning. Global syntheses have shown that conservation tillage can increase microbial biomass and microbial counts, although the magnitude and direction of response depend on soil texture, residue management, climate and duration of conservation practices (Chen *et al*., 2020; Li *et al*., 2020).
Weed interference is therefore a major constraint to maize productivity under conservation agriculture. Zero tillage may favour persistence of weeds adapted to reduced soil disturbance, whereas residue mulch can modify light interception, soil temperature and moisture at the soil surface. In zero-till maize, pre-emergence pendimethalin and post-emergence tembotrione have been evaluated as practical options for controlling mixed weed flora and appropriate herbicide programmes can substantially reduce weed biomass and protect grain yield (Mitra *et al*., 2018; Triveni *et al*., 2017). Field studies have also demonstrated that tillage and weed-management practices can jointly influence weed dynamics and maize productivity (Stanzen *et al*., 2016; Rani *et al*., 2022). The choice of weed-management strategy is particularly important because weeds not only compete with maize for light, water and nutrients but also accumulate substantial quantities of N, P and K in their biomass. Effective

weed suppression can consequently reduce temporary nutrient capture by weeds and improve the opportunity for nutrient acquisition by maize. Chopra and Angiras (2008) demonstrated that effective weed control in maize increased crop N, P and K uptake while reducing nutrient depletion by weeds. Similar responses to chemical weed management have been reported in maize under different production environments (Triveni *et al*., 2017; Rani *et al*., 2022).

At the same time, herbicide use introduces a soil-biological dimension to weed management. Bacteria, fungi and actinomycetes participate in decomposition and nutrient cycling and their abundance can respond to tillage, residue inputs, soil moisture and pesticide exposure. A global meta-analysis showed that no-tillage and residue retention generally increased microbial counts compared with conventional tillage, with particularly positive responses under residue-retained systems (Li *et al*., 2020). More recent evidence from conservation-agriculture maize systems confirms that tillage and herbicide regimes can alter microbial and fungal indicators (Nthebere *et al*., 2025), while a recent meta-analysis indicates that pesticide effects on soil microbial indicators are compound- and context-dependent (Swaine *et al*., 2025). Residue retention can therefore provide an additional biological advantage in conservation agriculture. Surface residues supply carbon substrates and modify the soil microclimate, potentially favouring microbial colonization and activity. Global syntheses report increases in microbial biomass C and N under no-tillage plus residue retention (Li *et al*., 2018) and increases in fungal and bacterial biomass under conservation tillage (Chen *et al*., 2020). Recent rice–maize research similarly reports improvements in soil organic carbon and microbial biomass under residue-retained conservation practices (Sahoo *et al*., 2025).

The agronomic assessment of conservation agriculture should consequently integrate weed suppression, soil biological responses and crop productivity rather than treating these components independently. The present experiment provides such a combined assessment by comparing conventional tillage, zero tillage with paddy-straw mulch and zero tillage without mulch under four contrasting weed-management strategies. Although studies have separately examined tillage, residue retention, herbicide efficacy and soil microbial responses in maize, fewer experiments report these components together under the same split-plot field experiment. The present study therefore focuses specifically on weed biomass, weed N–P–K capture, culturable soil microbial populations and maize productivity, thereby providing a more integrated interpretation of weed management under conservation tillage. Recent advances in precision weed management, including UAV-based weed detection and site-specific weed control, offer additional opportunities to improve the efficiency and sustainability of weed-management programmes in conservation agriculture (Banoth *et al*., 2025). Therefore, the present investigation was undertaken to evaluate the influence of three tillage systems and four weed-management practices on (i) weed biomass, (ii) nutrient capture by weeds, (iii) culturable populations of soil bacteria, fungi and actinomycetes and (iv) maize grain and stover productivity. Particular emphasis was placed on whether residue-retained zero tillage could maintain maize productivity while supporting a more biologically active soil environment.

MATERIALS AND METHODS

The field experiment was conducted at AICRP on Weed Management Block, Central Farm, Department of Agronomy, Odisha University of Agriculture & Technology (OUAT), Bhubaneswar, Odisha during *rabi* 2020-21. The experiment consists seven treatments Conventional Tillage (CT), Zerotillage+Mulching (ZT+M) (paddy straw @5t ha^{-1}) and Zero Tillage (ZT-dibbling) assigned in main plots and Pendimethalin (pre-emergence@ 1 kg ha^{-1}), Tembotrione (post-emergence@ 120 g ha^{-1}), Manual weeding and Weedy check in subplots in a split plot design and replicated thrice. In zero tillage and Zero tillage + mulching, sowing was done by opening a small furrow to place seed with the power tiller operated zero till drill without disturbing the soil and leaving about 5-10% previous rice crop residue of 5t ha^{-1} in Zero tillage + mulching. In Conventional tillage, the land was first ploughed with disc plough followed by 2-3 times harrowing and planking. The soil was sandy loam in texture with pH 5.6, bulk density of1.5 Mg m^3, organic carbon 6.3g kg^{-1}, available nitrogen 218.28 kg ha^{-1}, phosphorus 21.36 kg ha^{-1} and potassium 127.28 kg ha^{-1}.

Weed biomass was recorded from four randomly selected 0.5 × 0.5 m quadrats in each plot at 30 DAS, 60 DAS and harvest. Weeds were cut close to the ground, shade dried and then oven dried at 80°C to constant weight. Weed biomass was expressed as g m^{-2}. Where required, $\sqrt{(x+1)}$ transformation was applied before analysis. Weed control index was calculated from the reduction in weed biomass relative to the corresponding weedy check. For nutrient analysis, maize grain and stover samples and weed samples were collected from each plot at harvest. Samples were oven dried at 80°C for 72 h, ground and passed through a 2-mm sieve before chemical analysis. Nitrogen, phosphorus and potassium uptake or capture were expressed on an area basis (kg ha^{-1}). Soil microbial populations were estimated by serial dilution and spread plating using nutrient agar for bacteria, rose bengal agar for fungi and actinomycetes isolation agar for actinomycetes. Plates were incubated at 30°C; bacteria and fungi were enumerated after 24 h and actinomycetes after 48 h. The counts are therefore culturable populations and should not be interpreted as total microbial diversity or whole-soil microbiome abundance. Data were analysed according to the split-plot design and SEm± and CD at P=0.05 were used for mean comparison.

3. RESULTS AND DISCUSSION

3.1 Weed biomass under contrasting tillage and weed-management practices

Tillage significantly influenced weed biomass at all observation stages (Table 1 and Fig. 1). Conventional tillage recorded the lowest weed biomass of 22.19, 17.22 and 36.04 g m^{-2} at 30 DAS, 60 DAS and harvest, respectively, whereas ZT recorded the highest values of 25.26, 20.24 and 37.97 g m^{-2}. ZT+M remained intermediate (24.08, 18.76 and 36.74 g m^{-2}). The lower biomass under CT is consistent with the greater soil disturbance associated with repeated tillage, which can bury or expose weed seeds and destroy newly emerged seedlings. Similar differences in weed dynamics between tillage systems have been reported in maize-based systems (Gul *et al*., 2011; Stanzen *et al*., 2016). In contrast, residue retention under ZT+M partially moderated weed biomass relative to residue-free ZT, indicating that the mulch layer may have altered the soil-surface environment and suppressed part of the emerging weed population.

Among weed-management practices, pendimethalin produced the lowest weed biomass at all three stages (22.57, 14.57 and 34.48 g m^{-2}), closely followed by tembotrione (22.79, 15.41 and 35.21 g m^{-2}). Manual weeding resulted in 24.07, 16.24 and 36.15 g m^{-2}, whereas the weedy check accumulated 25.95, 28.73 and 41.81 g m^{-2}. Thus, the largest divergence among weed management treatments occurred at 60 DAS and harvest, when uncontrolled weeds had sufficient time to accumulate biomass. The efficacy of pre- and post-emergence herbicides in reducing weed biomass in maize is consistent with results reported by Mitra *et al*. (2018), Triveni *et al*. (2017) and Rani *et al*. (2022).

Table 1. Effect of tillage and weed-management practices on weed biomass (g m^{-2}).

Treatments	30 DAS	60 DAS	At harvest
Main plot (Tillage)			
T_1 – Conventional tillage (CT)	22.19	17.22	36.04
T_2 – Zero tillage + mulching (ZT+M), paddy straw @ 5 t ha^{-1}	24.08	18.76	36.74
T_3 – Zero tillage (ZT), dibbling	25.26	20.24	37.97
SEm±	0.14	0.21	0.38
CD (P=0.05)	0.53	0.81	1.49
Sub plot (Weed management)			
W_1 – Pendimethalin, pre-emergence @ 1 kg ha^{-1}	22.57	14.57	34.48
W_2 – Tembotrione, post-emergence @ 120 g ha^{-1}	22.79	15.41	35.21
W_3 – Manual weeding	24.07	16.24	36.15
W_4 – Weedy check	25.95	28.73	41.81
SEm±	0.26	0.62	0.94
CD (P=0.05)	0.76	1.83	2.80

The weed-control pattern is also reflected in the weed control index: CT recorded 82.39%, followed by ZT+M (72.64%) and ZT (64.64%); among weed-management treatments, pendimethalin recorded 80.28%, followed by tembotrione (74.64%) and manual weeding (68.18%). Because weed density and weed-control efficiency have already been reported in the related published work from this experiment, the present article emphasizes biomass as the primary weed-response variable to minimize duplication. The present biomass results nevertheless support the established observation that early chemical weed suppression is particularly important in zero-till maize (Mitra *et al*., 2018).

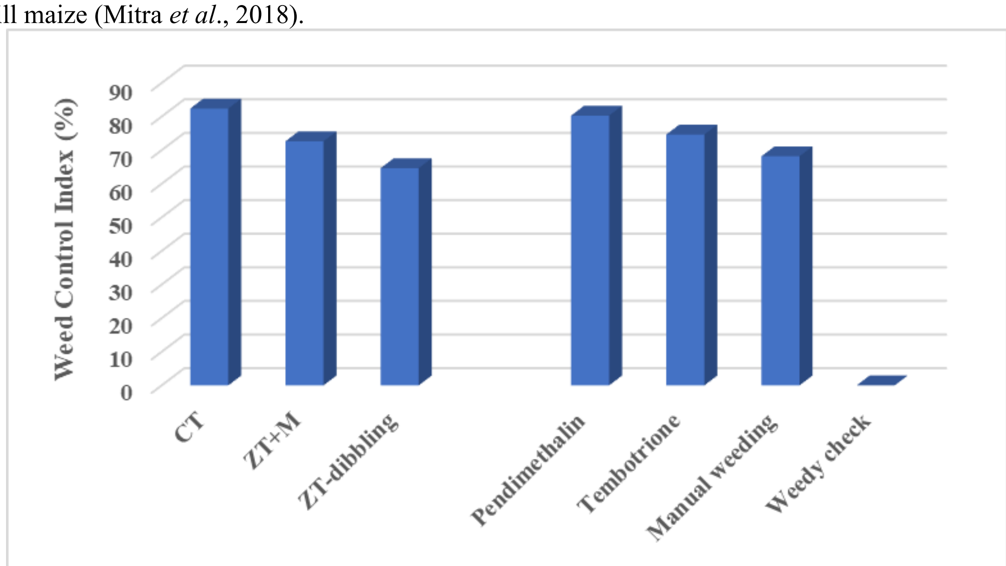

Fig. 1 Effect of tillage and weed management practices on weed control index

3.2 Nutrient capture by weeds

Tillage altered the amount of N, P and K contained in weed biomass (Table 2). At 30 DAS, weed N capture ranged from 21.87 kg ha^{-1} under CT to 23.83 kg ha^{-1} under ZT; corresponding P capture ranged from 3.61 to 4.88 kg ha^{-1} and K capture from 24.06 to 27.34 kg ha^{-1}. At 60 DAS, ZT recorded 32.87 kg N, 5.33 kg P and 26.55 kg K ha^{-1}, compared with 28.38, 4.68 and 24.25 kg ha^{-1} under CT. At harvest, the highest nutrient capture under ZT reached 45.21 kg N, 7.43 kg P and 39.56 kg K ha^{-1}, whereas CT recorded 39.58, 6.45 and 38.22 kg ha^{-1}, respectively. ZT+M was intermediate for N and P but approached ZT for K capture. This indicates that residue-retained ZT and residue-free ZT should not be treated as biologically identical systems: residue retention can modify the soil microenvironment and nutrient cycling even when the degree of soil disturbance is similar.

Weed-management treatments produced a much stronger gradient in nutrient capture. Pendimethalin restricted weed nutrient capture throughout the season. At harvest, N, P and K capture under pendimethalin were 34.22, 5.19 and 31.42 kg ha^{-1}, respectively, compared with 56.36, 10.50 and 50.65 kg ha^{-1} under the weedy check. These represent reductions of approximately 39.3% for N, 50.6% for P and 38.0% for K relative to the weedy check. Tembotrione also reduced nutrient capture, but its harvest values (35.65 kg N, 5.40 kg P and 32.22 kg K ha^{-1}) were slightly higher than pendimethalin. Manual weeding recorded intermediate-to-high values (42.92 kg N, 6.55 kg P and 41.24 kg K ha^{-1}). These results agree with the broader maize literature showing that effective weed suppression reduces nutrient depletion/capture by weeds and increases the opportunity for crop nutrient acquisition (Chopra and Angiras, 2008; Rani *et al*., 2022). Importantly, nutrient capture by weeds should be interpreted as temporary interception within the weed biomass rather than as an irreversible nutrient loss, because nutrients may subsequently return to the soil through weed decomposition.

Table 2. Effect of tillage and weed-management practices on N, P and K capture by weeds (kg ha^{-1}).

Treatment	N 30 DAS	P 30 DAS	K 30 DAS	N 60 DAS	P 60 DAS	K 60 DAS	N harvest	P harvest	K harvest
Main plot: CT	21.87	3.61	24.06	28.38	4.68	24.25	39.58	6.45	38.22
Main plot: ZT+M	22.63	3.92	25.75	30.89	4.98	25.29	42.08	6.85	38.88
Main plot: ZT	23.83	4.88	27.34	32.87	5.33	26.55	45.21	7.43	39.56
SEm± (tillage)	0.22	0.28	0.75	0.62	0.03	0.22	0.99	0.09	0.24
CD (P=0.05)	0.87	1.11	2.95	2.45	0.12	0.88	3.89	0.34	0.92
Sub plot: Pendimethalin	16.11	2.34	21.47	22.07	2.57	16.70	34.22	5.19	31.42
Sub plot: Tembotrione	17.18	3.13	22.53	23.31	2.81	17.28	35.65	5.40	32.22
Sub plot: Manual weeding	26.74	4.69	27.57	33.86	5.53	28.14	42.92	6.55	41.24
Sub plot: Weedy check	31.07	6.38	31.30	43.62	9.07	39.34	56.36	10.50	50.65
SEm± (weed management)	0.39	0.20	0.79	0.61	0.05	0.31	0.69	0.18	0.32
CD (P=0.05)	1.16	0.60	2.36	1.81	0.15	0.92	2.04	0.52	0.94

3.3 Culturable soil microbial populations

Culturable bacterial, fungal and actinomycete populations increased from 7 to 21 DAS under all tillage and weed-management treatments, but their magnitude differed among treatments (Table 3). ZT+M consistently recorded the largest microbial counts among the three tillage systems. At 21 DAS, bacterial, fungal and actinomycete populations under ZT+M were 75, 21 and 11 $\times 10^3$ CFU g^{-1} soil, respectively, compared with 57, 14 and 9 $\times 10^3$ CFU g^{-1} under CT. Thus, relative to CT, ZT+M increased the observed culturable bacterial, fungal and actinomycete counts by approximately 31.6, 50.0 and 22.2%, respectively. This pattern agrees with global evidence that residue retention and reduced soil disturbance can favour microbial abundance, although the magnitude of response is context-dependent (Chen *et al*., 2020; Li *et al*., 2020).

The weed-management treatments showed a different pattern. At 21 DAS, the weedy check recorded the largest bacterial, fungal and actinomycete populations (82, 22 and 14 $\times 10^3$ CFU g^{-1} soil), followed by manual weeding (76, 20 and 13 $\times 10^3$ CFU g^{-1}), tembotrione (65, 14 and 5 $\times 10^3$ CFU g^{-1}) and pendimethalin (44, 15 and 8 $\times 10^3$ CFU g^{-1}). The lower culturable bacterial count under pendimethalin relative to the weedy check was about 46.3%. These data indicate an association between weed presence, biomass and culturable microbial abundance in the short observation window, potentially because living weeds and decomposing weed residues provide organic substrates. However, the experiment did not quantify microbial biomass C, respiration, enzyme activities, functional genes or community composition; therefore, the observed plate counts should not be interpreted as a complete measure of soil microbiome health. This distinction is important because pesticide effects on soil microbial indicators can vary with compound, soil conditions, exposure and microbial endpoint (Swaine *et al*., 2025).

Table 3. Effect of tillage and weed-management practices on culturable soil microbial population (CFU ×10^3 g^{-1} soil).

Treatment	Bacteria 7	Bacteria 14	Bacteria 21	Fungi 7	Fungi 14	Fungi 21	Actino 7	Actino 14	Actino 21
Main plot: CT	52	55	57	10	11	14	8	9	9
Main plot: ZT+M	72	74	75	17	19	21	10	11	11
Main plot: ZT	65	67	68	15	17	19	9	9	10
SEm± (tillage)	3.08	1.67	1.67	0.99	0.50	0.05	0.05	0.17	0.29
CD (P=0.05)	12.07	6.54	6.54	3.87	1.97	0.19	0.19	0.65	1.13
Sub plot: Pendimethalin	40	42	44	10	13	15	6	7	8
Sub plot: Tembotrione	62	64	65	12	10	14	7	7	5
Sub plot: Manual weeding	73	75	76	16	18	20	11	12	13
Sub plot: Weedy check	78	80	82	18	20	22	12	13	14
SEm± (weed management)	2.72	1.92	2.72	0.66	0.85	0.08	0.06	0.37	0.35
CD (P=0.05)	8.09	5.72	8.09	1.96	2.52	0.23	0.17	1.09	1.04

3.4 Maize productivity and treatment interaction

Grain yield was 5354.33 kg ha^{-1} under CT, 5292.33 kg ha^{-1} under ZT+M and 4727.75 kg ha^{-1} under ZT. The CT and ZT+M treatments were statistically at par according to the thesis, whereas residue-free ZT recorded the lowest yield (Table 4 and Fig. 2). The relatively small difference between CT and ZT+M is agronomically relevant because ZT+M also supported the highest culturable microbial populations. Among weed-management treatments, pendimethalin recorded 5521.78 kg ha^{-1} grain yield, followed by tembotrione (5318.33 kg ha^{-1}), manual weeding (5072.44 kg ha^{-1}) and the weedy check (4586.67 kg ha^{-1}). The corresponding stover yields were 8915.22, 8778.56, 8470.78 and 7745.33 kg ha^{-1}, respectively. Effective weed suppression therefore coincided with higher crop productivity, consistent with previous maize studies evaluating pre- and post-emergence herbicides (Mitra *et al*., 2018; Triveni *et al*., 2017).

The tillage × weed-management interaction for grain yield was significant. The highest combination mean was obtained with CT + pendimethalin (T_1W_1; 5837.67 kg ha^{-1}), followed by ZT+M + pendimethalin (T_2W_1; 5641.67 kg ha^{-1}). The complete interaction matrix is retained below because the interaction is central to interpreting herbicide performance under conservation tillage. The thesis reports T_1W_1 as statistically at par with T_2W_1, T_1W_2 and T_2W_2. This indicates that residue-retained ZT combined with effective early weed suppression was capable of approaching the grain yield obtained under conventional tillage in this single-season experiment. Similar evidence from conservation-agriculture maize systems emphasizes the importance of matching establishment/tillage systems with an effective weed-control programme rather than evaluating tillage alone (Mitra *et al*., 2018; Nthebere *et al*., 2025).

Table 4. Effect of tillage and weed-management practices on maize grain yield, stover yield and harvest index.

Treatment	Grain yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Harvest index (%)
Main plot: CT	5354.33	8730.50	37.96
Main plot: ZT+M	5292.33	8677.92	37.84
Main plot: ZT-dibbling	4727.75	8024.00	37.05
SEm±	64.95	58.97	0.35
CD (P=0.05)	254.96	231.46	1.39
Sub plot: Pendimethalin	5521.78	8915.22	38.22
Sub plot: Tembotrione	5318.33	8778.56	37.71
Sub plot: Manual weeding	5072.44	8470.78	37.41
Sub plot: Weedy check	4586.67	7745.33	37.14
SEm±	83.74	30.90	0.36
CD (P=0.05)	248.76	91.80	1.0767

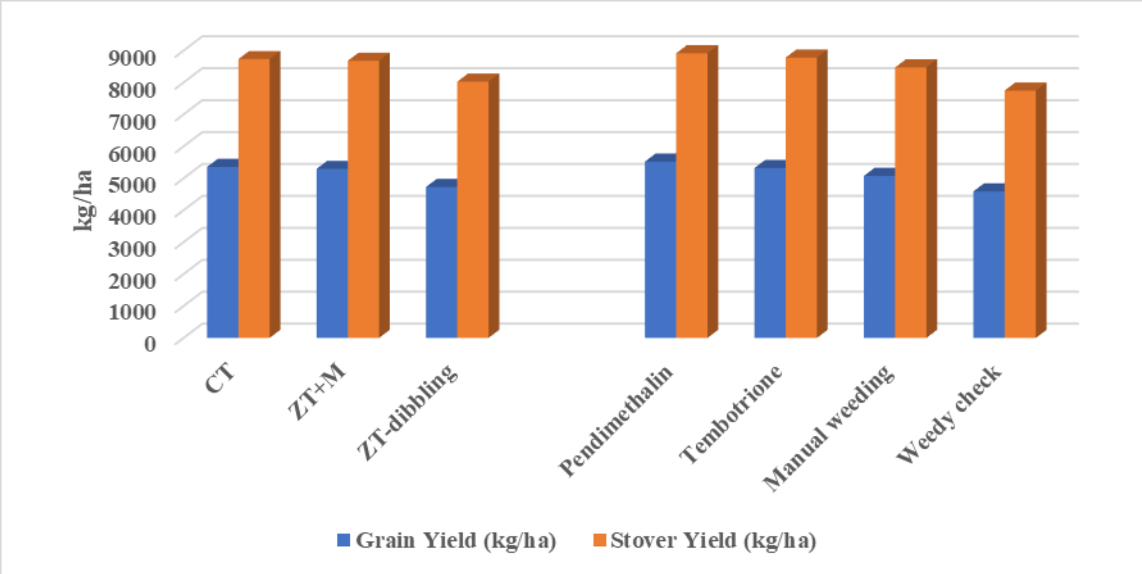

Figure 2. Effect of tillage and weed-management practices on maize grain yield and stover yield.

Table 5. Interaction effect of tillage and weed-management practices on maize grain yield (kg ha^{-1}).

Tillage × Weed management	**W_1 Pendimethalin**	**W_2 Tembotrione**	**W_3 Manual weeding**	**W_4 Weedy check**
T_1 CT	5837.67	5501.67	5309.00	4769.00
T_2 ZT+M	5641.67	5480.67	5295.33	4751.67
T_3 ZT	5086.00	4972.67	4613.00	4239.33
SEm± (T×W)	163.28	-	-	-
SEm± (W×T)	145.03	-	-	-
CD (P=0.05) (T×W)	517.95	-	-	-
CD (P=0.05) (W×T)	430.87	-	-	-

3.5 Integrated interpretation

The combined evidence demonstrates a clear management trade-off within the single-season experiment (Table 5). Conventional tillage produced the lowest weed biomass and the highest mean grain and stover yield, whereas ZT+M produced comparable maize yield while supporting the highest culturable populations of bacteria, fungi and actinomycetes. Residue-free ZT had both the highest weed biomass among the tillage treatments and the lowest grain yield. This pattern suggests that the biological benefits associated with reduced soil disturbance were more evident when residue was retained. Global meta-analyses similarly show that residue retention can enhance microbial biomass and microbial counts under conservation tillage, although responses depend on soil and environmental conditions (Chen *et al*., 2020; Li *et al*., 2020).

The weed-management results further indicate that weed suppression and soil microbial response need to be considered together. Pendimethalin minimized weed biomass, weed N–P–K capture and produced the highest mean grain and stover yields, but it also showed the lowest culturable bacterial population among the four weed-management treatments at 21 DAS. The weedy check showed the opposite pattern: the highest microbial counts occurred alongside the greatest weed biomass, nutrient capture and lowest maize yield. Thus, a high microbial count in the weedy check should not be interpreted as evidence of superior agronomic soil health; it may partly reflect greater plant-derived carbon inputs from unmanaged weeds. Conversely, the lower plate counts following herbicide treatment do not, by themselves, establish adverse long-term effects on soil biological functioning. Recent evidence emphasizes that pesticide responses are dependent on the microbial endpoint measured and the environmental context (Swaine *et al*., 2025), while maize conservation-agriculture research has demonstrated that tillage and herbicide combinations can alter microbiological indicators over time (Nthebere *et al*., 2025).

The present dataset therefore supports an integrated interpretation rather than a single-parameter recommendation: residue-retained zero tillage maintained maize productivity close to conventional tillage while providing a more favourable environment for culturable microbial populations, but it required effective weed suppression. The strongest yield response occurred when pendimethalin was combined with CT or ZT+M. Because the experiment covered one rabi season and microbial assessment was based on culturable plate counts, longer-term multi-season experiments incorporating microbial biomass C, enzyme activities, molecular community profiling and herbicide-residue dynamics would be needed to determine persistence and functional consequences.

Beyond weed suppression and crop productivity, conservation-agriculture practices should also be evaluated from the perspective of resource-use efficiency and environmental sustainability. Kumar *et al*. (2024)

demonstrated that tillage and weed-management strategies in maize–wheat systems substantially influenced productivity, energy-use efficiency and carbon footprint. Their findings emphasize that weed-management decisions should be considered together with the broader resource-use and environmental consequences of the production system. In the present study, although energy use and carbon footprint were not quantified, the observed differences in tillage, residue retention and herbicide-based weed suppression provide a basis for future assessment of these sustainability indicators.

3.6 Study limitations and scope for further research

Three limitations should be considered when interpreting the findings. First, the experiment was conducted during one rabi season (2020-21), so treatment responses should not be generalized to all seasons or soil environments. Second, microbial observations were based on culturable bacteria, fungi and actinomycetes and therefore represent only the culturable fraction of the soil microbial community. Third, nutrient capture by weeds represents nutrients contained in harvested weed biomass and should not automatically be equated with permanent nutrient loss from the soil. These limitations do not affect the validity of the treatment comparisons within the experiment, but they define the scope of inference and identify useful directions for longer-term conservation-agriculture research.

4. CONCLUSION

The experiment demonstrated that tillage and weed-management practices jointly influenced weed biomass, weed nutrient capture, culturable soil microbial populations and maize productivity. Conventional tillage reduced weed biomass and produced the highest mean maize grain yield, whereas zero tillage with paddy-straw mulch maintained statistically comparable grain yield and supported the highest culturable populations of bacteria, fungi and actinomycetes. Pendimethalin @ 1 kg ha^{-1} as pre-emergence produced the lowest weed biomass and weed N-P-K capture and the highest mean grain and stover yields among the weed-management treatments. The significant tillage × weed-management interaction showed that CT + pendimethalin produced 5837.67 kg ha^{-1} grain yield, while ZT+M + pendimethalin produced 5641.67 kg ha^{-1}. Overall, the results indicate that residue-retained zero tillage can maintain maize productivity when coupled with effective early-season weed suppression, while also supporting a larger culturable microbial population than conventional tillage. Further multi-season studies using microbial biomass, enzyme activities and molecular community indicators are warranted to confirm the longer-term biological implications of herbicide use under conservation agriculture.

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