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Research Paper

Selectivity of new generation herbicide 'Tembotrione' under conservation agriculture-based maize (*Zea mays*) in maize-wheat-mungbean cropping system

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ABSTRACT

An experiment was conducted at the ICAR-Indian Agricultural Research Institute in New Delhi during the rainy (*Kharif*) seasons of 2021–22 and 2022–23. The study aimed to evaluate the weed control efficiency of low dose new generation herbicide: tembotrione (34.4% SC) as a component of integrated weed management (IWM), on zero-till (ZT) and conventional till (CT) maize (*Zea mays* L.). The treatments were comprised of conventional tillage maize (M1: CT-M), conventional tillage maize with green manure from preceding green gram (M2: CT-M+GM), zero tillage maize with residue retention at 3 t/ha (M3: ZT-M+R), zero tillage maize with *Sesbania* co-culture as brown manuring (cover crop) (M4: ZT-M+BM) in the main plot and five weed control treatments, *viz* S1: Un-weeded check, S2: Pre +1 HW, S3: Pre + Post (tembotrione) @120g/ha, S4: Pre+ Post (Premix of Mesotrione+ Atrazine) @120 g/ha, S5: Weed free check (WFC) in the sub-plots were evaluated in split-plot design. It was observed that ZT-M+BM caused a considerable reduction in the population of broad-leaf weed, narrow leaf weed with sedges and total weeds (28.4% reduction at 60 days after sowing) compared to M1. The results also revealed that the sequential application of atrazine @750g/ha+pendimethalin @750g/ha(pre) followed by (fb.) tembotrione (34.4% SC) @120 g/ha (post) among the herbicide options reduced the weeds population (78.5%) and dry weight (81.3%) significantly than the un-weeded control (UWC). Maize yield attributes were higher in ZT with *Sesbania* co-culture (ZT-M+BM) than conventional-tilled treatments (CT-M). The application of atrazine @750g/ha+pendimethalin @750g/ha (pre) *fb*. tembotrione @120 g/ha (post) combined with ZT-M+BM resulting in higher maize yield (6.88 t/ha) which was comparable with that in weed-free check (WFC). The post emergence (PoE) application of tembotrione (34.4% SC) @120 g/ha recorded highest weed control efficiency (86.2%), weed control index (88.1%) and lowest value of weed index (7.04) when applied in the ZT-maize with *sesbania* as a cover crop. Therefore, combining zero tillage (ZT) with brown manure (*Sesbania*), along with atrazine and pendimethalin (@750g/ha each) as pre-emergence herbicides, and tembotrione (@120g/ha) as a post-emergence herbicide is recommended for effective weed control and high maize productivity in the North-Western Indo-Gangetic plains (IGP).

Key words: Brown manuring, Cover, Conservation agriculture, Crop, HPPD-inhibitor, Integrated weed management, Tembotrione

The global adoption of conservation agriculture (CA) aims for sustainable crop production systems to feed the worlds growing population (8 billion) and enhance ecosystem services (Giller *et al.,* 2015). CA faces challenges in crop establishment and weed management, especially under zero tillage (ZT) due to surface residue issues in early conversion years (1 to 3 years) (Soni *et al.,* 2020). Integrating diverse cropping systems, advanced weed management techniques with new generation herbicides, and improving the crop establishment methods are crucial for CA-based maize (*Zea mays* L.) cultivation. The continuous rice–wheat system (RWS) also faces weed shift issues, particularly small canary grass (*Phalaris minor*) in wheat and Bermuda grass (*Echinochloa colona*) in rice (Singh and Singh, 2005). The maize-wheat system, covering over 1.83 million ha under zero-till with residue retention, is advocated for higher productivity (Shekhawat *et al.,* 2021). In Asia, cropping patterns are rapidly changing due to increased maize demand (Yakadri *et al.,* 2015). Maize is versatile crop, adapting well to various agro-climatic conditions, and accounts for about 9% of India's national food security. It ranks third after rice and wheat as a crucial

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cereal crop (Dass *et al.*, 2018). The rising poultry and animal feed industries are driving higher maize grain demand (Shyam *et al.,* 2021; Singh *et al*., 2018).

Maize productivity in India (2689 kg/ha) is significantly lower than the global average (5500 kg/ha), indicating a considerable gap (Singh *et al*., 2018). Weeds are a major factor in this yield reduction, posing challenges in conservation agriculture (CA), especially with zero-till drills. This issue is acute in the Indo-Gangetic Plains (IGP) due to the scarcity of post-emergence herbicides. Available herbicides like atrazine, oxyfluorfen, 2,4-D, and pendimethalin mainly target broadleaf weeds, leaving grasses and sedges difficult to control, particularly under extreme soil moisture and labour shortages (Swetha *et al.,* 2015). Tillage modifications also affect weed seed dynamics, weed seeds are often concentrated in the topsoil of no till system (Mulugeta and Stoltenberg, 1997). Weed competition can reduce maize yields by up to 90% (Dalley *et al.,* 2006), with reported reductions ranging from 40% to 80% (Reddy and Tyagi, 2005). Herbicides are crucial for weed management in CA systems (Bhullar *et al.,* 2016). Traditional weed control involves manual weeding and spading, creating ridges and furrows 4-5 weeks post-seeding, demanding significant labour due to the slow initial growth and wide row spacing (60 cm).

Therefore, this research aimed to validate suitable tillage methods along with a sequential application of new generation herbicides such as tembotrione, which has a low application rate and operates through a different mode of action (HPPD inhibitor), or the use of cover crops to reduce weed growth. Additionally, the study aimed to highlight the benefits of zero tillage compared to conventional tillage practices.

MATERIALS AND METHODS

***Location of experimental site, experimental design and environmental conditions*:** A field experiment was carried out during the rainy (*Kharif*) season of 2021–22 and 2022–23 at the ICAR-Indian Agricultural Research Institute (28°08’N latitude,77°12’ E longitude and at an elevation of 228.61 metres (750 feet) above mean sea level) New Delhi, India, in a split plot design (SPD) with 3 replications, comprising of 4 tillage methods in main plot and 5 weed-control treatments in sub-plot in maize. The research farm’s semi-arid climate features dry, hot summers (May-June) with temperatures between 40° and 45°C, and cold winters (December-January) with lows around 2°C. Annual rainfall averages 650 mm, mostly between July and September. The yearly pan evaporation rate is about 850 mm. Wind speeds average 7.6 km/h in April and 3.5 km/h in October. During the rainy season, relative humidity ranges from over 90% to 45%.

***Treatment Details*:** The treatments were comprised of four tillage methods *viz* conventional tillage maize (M1: CT-M), conventional tillage maize with green manure from preceding green gram (M2:CT-M+GM), zero tillage maize with residue retention at 3t/ha (M3: ZT-M+R), zero tillage maize with *Sesbania* co-culture as brown manuring/cover crop (M4: ZT-M+BM) in main plot and five weed control treatments, *viz* S1: Un-weeded check (UWC), S2: Pre (atrazine + pendimethalin @750g/ha, each) +1 Hand weeding (25 DAS), S3: Pre (atrazine + pendimethalin @750g/ha, each) + Post (tembotrione) @120g/ha, S4: Pre (atrazine + pendimethalin @750g/ha, each)+Post (Premix of mesotrione + atrazine) @120g/ha, S5: Weed free check in sub-plots were evaluated. Atrazine @ 750g/ha + pendimethalin @ 750g/ha as pre-emergence (day after sowing) and tembotrione @ 120 g/ha as post-emergence (30 DAS) were applied separately in the needed amount with 400 litres of water/ha by knapsack sprayer for sequential application of herbicides. A knapsack sprayer equipped with a flat-fan nozzle was used to apply @120g/ha of the ready-mix herbicide (Mesotrione 2.27%W/w + Atrazine 22.7%W/w) at 30 days after sowing (DAS).

***Soil quality of experimental site*:** Soil of experimental site was sandy loam, with pH 7.5, low in organic C (0.32%), low in available N (148.4 kg/ha), high in P (30.8 kg/ha) and medium K (256.4 kg/ha). During the winter season (*Rabi*), wheat crop was cultivated with the stipulated treatments, and the leftover crop residues were applied in the subsequent rainy season (kharif) for maize cultivation. Following the wheat harvest, mung bean was cultivated as a green manure crop and then incorporated into the field as per the designated treatment.

***Field Preparation and agronomic practice*:** The main plots were prepared in accordance with specific requirements, and within each main plot, five subplots were established to accommodate various methods of weed control, so the total plot number was 60 (4 main plot × 5 sub plot × 3 replication). In the conventional tillage (CT) plots, a tractor-drawn disc plough was used for ploughing, followed by levelling with a planker. For zero tillage (ZT) plots with residues, the residue from the previous wheat crop was kept intact, while ZT plots without residues were left undisturbed. Additionally, a weed-free check was maintained, involving manual weeding carried out at intervals of 30, 60, and 90 days after sowing (DAS). On the same day as maize sowing, *Sesbania aculeata* L., a leguminous cover crop, was broadcasted at a rate of 15 kg/ha. This cover crop served the purpose of suppressing weeds during the early stages of maize growth and also acted as a source of brown manure. On the 30th day after sowing, the *Sesbania aculeata* was sprayed with 2,4-D herbicide at a rate of 0.25 kg/ha. After this treatment, the browncoloured residues of *Sesbania* were composted. Seeds of the 'PJMH-1' hybrid maize, with a growth duration of 100-110 days, were sown using a 9-tyne zero-till seed drill, maintaining a spacing of 60 cm between lines and a seed-to-seed interval of 20 cm. A calculated amount of nutrients, specifically 120-60-40 kg NPK/ha were applied on the basis of soil-test analysis in maize through urea, single superphosphate and muriate of potash, respectively.

Observations and statistical analysis: Weed species were counted from a 1m × 1m (1m^2) quadrat, and density was given in number/m^2. The weeds were first dried in the sun, then placed in an electric oven set to 70°C until the weight remained constant. The dry weight was then calculated as g/m^2. For microbial biomass carbon (MBC) and fluorescein diacetate (FDA) analysis, moist soil samples were collected from each plot at a 0–15 cm depth in the flowering stages. The samples were kept moist and tested for microbial activity on the same day. The benefit-cost ratio for each treatment was calculated as the ratio of net returns to the cost of cultivation. The data on yield attributes were taken at harvest from 5 randomly chosen plants. The data were analysed using analysis of variance (ANOVA) for a split plot design to determine the significance of overall treatment differences using the "F" test and conclusion was drawn at 5% probability level. To assess weed control efficacy (WCE), weed control index (WCI), and weed index (WI), the following calculations were made according to Das (2008):

$$WCE\ (\%) = \frac{(Weed\ density\ in\ Control\ plot - Weed\ density\ in\ treated\ plot)}{Weed\ density\ in\ control\ plot} \times 100$$

$$WCI\ (\%) = \frac{(Weed\ dry\ matter\ in\ Control\ plot - Weed\ dry\ matter\ in\ treated\ plot)}{Weed\ dry\ matter\ in\ control\ plot} \times 100$$

$$WI\ (\%) = \frac{(Crop\ yield\ in\ control\ plot - Crop\ yield\ in\ treated\ plot)}{Crop\ yield\ in\ control\ plot} \times 100$$

Two years data (2021-22 and 2022-23) were pooled before analysis. The standard error of the mean was calculated for each case. When the 'F' value from the ANOVA was significant, the least significant difference (LSD) was computed to test treatment significance. To address data variability, weed density and dry weight were normalized using the square-root [√(x+0.5)] transformation before ANOVA.

RESULTS AND DISCUSSION

Weed population and weed dry matter accumulation: In the experimental plot, a diverse array of annual and perennial weeds were observed, encompassing both grassy weeds and broad-leaved weeds, as well as sedges. Among the narrow-leaved weeds, *Setaria viridis* L., *Digitaria sanguinalis* L., and *Dactyloctenium aegyptium* L. On the other hand, among the broad-leaved weeds, the dominant species were *Commelina benghalensis* L., *Amaranthus viridis* L., *Trianthema portulacastrum* L., and *Digera arvensis* L. Additionally, among the perennial weeds, *Cyperus rotundas* L. and *Cynodon dactylon* L., were observed.

The study observed significant differences in total weed dry matter accumulation (g/m^2) among treatments at 30, 60, and 90 days after sowing (DAS), detailed in Table 1. Initially, at 30 DAS, the effect of tillage was predominant in contrast, 60 and 90 DAS, the herbicide application became notably effective. At 30 DAS, CT-M had the highest weed dry weight, whereas ZT-M+BM exhibited the greatest reduction (10.4%). Similar trends were observed at 60 DAS, indicating effective weed control with herbicide application. Treatment S3 (Pre + Post application of tembotrione) showed the lowest weed dry weight at 60 DAS (9.8 g/m²), followed by hand weeding (S2) (24.5 g/m²) and Premix Meso+Atra application (S4) (25.8 g/m²), compared to the un-weeded check. These findings underscore the efficacy of S3 and ZT-Maize + Sesbania brown manure in reducing weed dry weight significantly at 60 DAS and 90 DAS.

However, the count of BLW was higher (80.7%) in conventional tillage (CT-M) plots compared to zero tillage (ZT) plots, and also the perennial weed species like sedges were more abundant in ZT plots than in CT plots (Figure:1). The grassy weed *Cynodon dactylon* was most prevalent in ZT-M+BM among the different establishing techniques, with 6.5 No./m^2 followed by ZT-M+R. *Amaranthus viridis* was the predominant broad-leaved weed, and CT-M had the highest number of it (3.3 No./m^2), followed by CT-M+GM and ZT-M+R. *Cyperus rotundas* predominated among the sedges, particularly in ZT-M + R at 19.6 No./m^2 and ZT-M+BM and CT-M had the lowest count. The results demonstrate that *Sesbania* has a smothering effect as a cover crop, leading to a significant reduction in weed population at the experimental site. The S3 herbicide treatment, combining pre-emergence application of atrazine + pendimethalin (each @750g/ha) and post-emergence application of tembotrione (120g/ha) at 30

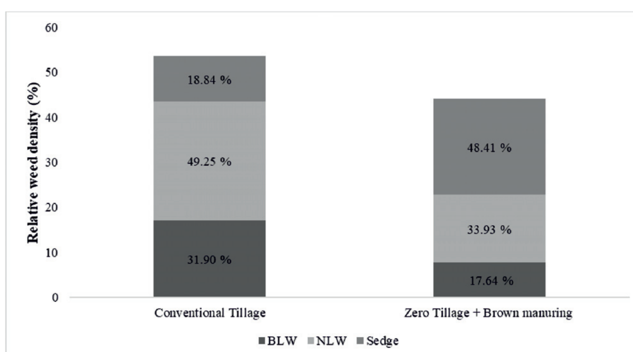


Fig. 1. Effect of crop establishment methods on weed distribution pattern in CT-M and ZT-M+BM plot
Where, BLW: Broad leave weed; NLW: Narrow leave weed;

Table 1. Effect of crop establishment methods and weed management on weed dry weight (g/m^2) in maize (Two years pooled data)

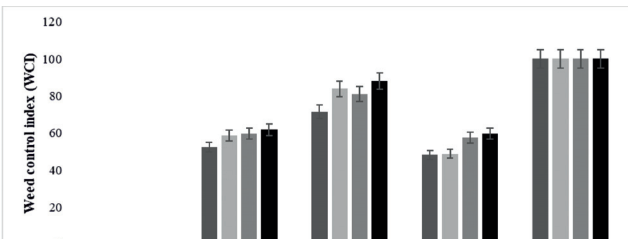
Treatment	30 DAS	60 DAS	90 DAS
Crop establishment methods			
CT-Maize	7.7(71.2)	4.6(26.2)	7.7(72.7)
CT-Maize + Green manure	7.4(65.4)	4.4(23.9)	7.5(68.2)
ZT-Maize + Residue*	7.6(69.4)	4.2(21.4)	7.2(64.2)
ZT-Maize + *Sesbania* Brown manure	7.3(63.8)	3.8(18.4)	6.9(59.3)
SEm±	0.1(1.3)	0.0(0.6)	0.1(2.5)
CD (P=0.05)	0.2(4.5)	0.1(2.1)	0.5(8.5)
Weed management options			
Un-weeded check	10.0(99.3)	7.2(52.3)	11.4(129.2)
Pre +1 HW	9.0(79.7)	5.0(24.5)	8.5(71.6)
Pre + Post (*Tembotrione)*	8.8(76.7)	3.2(9.8)	7.8(61.0)
Pre + Post (Premix *Meso+Atra*) §	9.1(81.6)	5.1(25.8)	8.3(69.0)
Weed free check	0.7(0.0)	0.7(0.0)	0.7(0.0)
SEm±	0.1(2.2)	0.1(0.8)	0.1(1.8)
CD (P=0.05)	0.3(6.3)	0.2(2.4)	0.3(5.3)

Note: CT, conventional tillage; ZT, zero tillage; * wheat residue @ 3t/ha; PRE, pre-emergence; POST, post-emergence; HW, hand weeding at 25 DAS; Tembo: tembotrione @ 120g/ha; §:pre-mix dose @ 120 g/ha. The data were subjected to square root transformation √x+0.5 before statistical analysis. Figures in parentheses are the original values.

DAS, significantly reduced weed density at 60 DAS for sedges (7.8/m²), narrow-leaf weeds (8.3/m²), broad-leaved weeds (3.9/m²), and total weeds (22.3/m²) as compared to the weed density of 30 DAS. In contrast, the un-weeded control (S1) had weed densities at 30 DAS of sedges (30.3/m²), grasses (31.9/m²), broad-leaved weeds (18.5/m²), and total weeds (80.8/m²), which increased further at 60 DAS (Table 2). This demonstrates that weed populations increased in the un-weeded control but decreased with the herbicide treatment, highlighting the effectiveness of tembotrione as a potent post-emergence herbicide.

The sequential application of atrazine @ 750 g/ha with pendimethalin @ 750 g/ha (pre) *fb*. tembotrione @ 120 g/ha (post) outperformed the other weed control techniques by considerably reducing the number of weed species (78.5% reduction over the weedy check) in comparison to S2 and S4. The decreased weed density (Table:2) and dry matter (Table:1) observed in these treatments could be attributed to the enhanced efficacy and extended impact of the applied HPPD-inhibiting herbicides. These herbicides not only curtailed weed growth but also led to a swift exhaustion of carbohydrate reserves in pre-germinated weeds. This depletion was facilitated by rapid respiration, leaf bleaching, reduced leaf area, and impaired photosynthesis. This finding is consistent with the studies conducted by Bollman *et al.*, (2008). According to Kumar *et al.* (2015), applying tembotrione (34.4% SC) post-emergence at a rate of 120 g/ha at 15 DAS resulted in a significant reduction in weed density and higher weed control efficiency.

Weed index (WI), Weed control index (WCI) and weed control efficiency (WCE): Weed index is a measure of crop yield loss. Lower weed index values indicate successful suppression of weed growth and competition, resulting in reduced weed density and dry weight in experimental plots (Das 2008). Among treatments, S3:(Pre+Post application of Tembotrione) with M4: ZT-Maize + Sesbania brown manure (M4) yielded the best weed index values (7.04 and 8.37), indicating superior weed control and potential yield enhancement. The results show that the highest yield was obtained in the M4×S3 plot, which recorded a 69.35% increase in yield compared to the un-weeded control (UWC) (Figure:4). 60 DAS and 90 DAS, the weed control efficiency (WCE) (Figure:3) and weed control index (WCI) (Figure:2) were calculated to assess the effectiveness of weed management practices. At 30 DAS, the



	S1	S2	S3	S4	S5
M1	0	52.4	71.4	48.3	100
M2	0	58.5	83.8	48.8	100
M3	0	59.8	81.1	57.5	100
M4	0	61.8	88.1	59.8	100

Fig. 2. Effect of crop establishment methods and weed management on Weed control index (WCI) at 60 DAS

M1: CT -Maize; M2: CT-Maize + Green manure; M3: ZT-Maize + Residue*; M4: ZT-Maize + Sesbania Brown manure; S1: Un-weeded check; S2: Pre (atrazine +pendimethaline @ 750g/ha) +1 HW at 25 DAS; S3: Pre (atrazine +pendimethaline @ 750g/ha) + Post (tembotrione @ 120g/ha); S4: Pre (atrazine +pendimethaline @ 750g/ha) + Post (Premix mesotrione+atrazine @120g/ha) § ; S5: Weed free check.

Table 2. Effect of crop establishment methods and weed management option on weed density (No./m^2) in maize (Two years pooled data)

Treatment	30 DAS				60 DAS				90 DAS			
	BLW	NLW	Sedge	Total	BLW	NLW	Sedge	Total	BLW	NLW	Sedge	Total
Crop establishment methods												
M_1	3.5(17.1)	4.7(26.4)	2.8(10.1)	3.8(57.6)	3.0(11.4)	4.5(21.3)	2.8(9.5)	6.3(49.7)	2.92(9.7)	5.34(33.6)	3.58(16.1)	6.98(59.5)
M_2	3.2(11.3)	4.8(27.1)	3.1(12.0)	2.6(50.4)	2.8(9.4)	4.0(19.5)	2.8(9.3)	5.7(41.7)	2.76(8.3)	5.40(34.9)	3.51(14.9)	6.91(58.2)
M_3	3.0 (9.8)	4.6(24.8)	4.5(25.1)	2.5(59.8)	2.6(7.7)	3.7(17.4)	3.7(19.6)	5.4(38.3)	2.45(6.5)	5.42(35.2)	3.61(16.7)	6.90(58.5)
M_4	2.7 (7.8)	4.1(15.0)	4.3(21.4)	2.4(44.2)	2.4(6.5)	3.4(15.0)	3.6(16.1)	5.3(35.6)	2.13(5.0)	5.12(31.6)	3.70(16.3)	6.60(53)
SEm±	0.1(0.7)	0.2(2.0)	0.3(2.6)	0.1(4.5)	0.1(0.5)	0.2(1.2)	0.1(1.4)	0.2(2.7)	0.07(0.4)	0.14(1.8)	0.37(3.4)	0.14(2.4)
CD (P=0.05)	0.3(2.3)	NS	0.9(9.1)	0.3(15.5)	0.4(1.9)	0.7(6.6)	0.5(4.8)	0.7(9.5)	0.25(1.4)	NS	NS	NS
Weed management options												
S_1	4.3(18.5)	5.6(31.9)	5.3(30.3)	4.8(80.8)	5.1(24.5)	7.0(42.6)	5.8(35.2)	10.3(103.5)	3.84(14.5)	7.6(57.5)	5.92(35.2)	10.36(107.2)
S_2	3.3 (10.8)	5.6(31.3)	4.2(19.3)	2.6(61.5)	2.8(7.4)	4.4(19.9)	3.6(13.3)	6.3(39.8)	2.83(7.8)	6.16(37.9)	3.88(15.7)	7.82(61.4)
S_3	3.6 (13.0)	5.1(26.3)	4.0(17.7)	2.0(56.9)	2.1(3.9)	2.8(8.0)	2.7(7.8)	4.7(22.3)	2.47(5.8)	5.80(33.9)	3.58(13.8)	7.33(53.6)
S_4	3.4 (11.5)	5.7(33.4)	4.1(18.4)	2.8(63.3)	2.9(7.9)	4.6(21.1)	3.4(11.9)	6.4(40.8)	2.99(8.7)	6.34(40.1)	3.90(15.5)	8.03(64.2)
S_5	0.7 (0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)
SEm±	0.1 (0.7)	0.3(2.9)	0.3(2.7)	0.1(4.5)	0.1(0.7)	0.2(2.3)	0.2(1.9)	0.2(3.3)	0.12(0.8)	0.19(2.4)	0.22(1.9)	0.19(3.1)
CD (P=0.05)	0.3(2.2)	0.7(8.4)	1.0(7.7)	0.4(13.0)	0.4(2.0)	0.7(6.6)	0.7(5.4)	0.7(9.6)	0.35(2.1)	0.55(6.8)	0.64(5.6)	0.56(8.8)

M_1, CT, Maize; M_2, CT, Maize + Green manure; M_3, ZT, Maize + Residue*; M_4, ZT, Maize + Sesbania Brown manure; S_1, Un-weeded check; S_2, Pre (atrazine + pendimethaline @ 750 g/ha) + 1 HW at 25 DAS; S_3, Pre (atrazine + pendimethaline @ 750 g/ha) + Post (tembotrione @ 120 g/ha); S_4, Pre (atrazine + pendimethaline @ 750 g/ha) + post (Premix mesotrione + atrazine @ 120 g/ha)$; S_5, Weed free check

The data were subjected to square root transformation √x+0.5 before statistical analysis. Figures in parentheses are the original values.

establishment effects and weed management effects did not have a significant impact. At 60 DAS, the weed-free check plot had the highest weed control index value of 100%. The Pre+Post tembotrione treatment (S3) combined with ZT-Maize + *Sesbania* Brown manure (M4) was the second most effective, with a WCI of 88.1%. Weed management practices recorded better WCE which ranged from 56.5 % to 86.2% at 60 DAS, 41.2% to 58.2% at 90 DAS. At 60 DAS, weed-free check plot showed highest efficiency in controlling the weeds showing a value of 100%. The sequential application of atrazine @750 g/ha with pendimethalin at 750 g/ha (pre), *fb* Tembotrione @120 g/ha (post) (S3) along with ZT+BM (M4) showed the second-best efficiency in terms of weed control efficiency by showing a value of 86.2%, followed by in the application of same herbicide in ZT+R plot which showed a value of 83.1%.

This might be due to higher efficacy of herbicides which resulted in lower weed density, weed dry weight along with the smothering effect of cover crop *Sesbania*. Similar reports of higher WCE with tank mix of HPPD inhibiting herbicides with atrazine have been given by Jonathon *et al.* (2013), Madhavi *et al.* (2014). At 90 DAS, the trends in WCE values remained consistent, the effect could be attributed to the pre-emergence application of pendimethalin or atrazine, which suppressed the initial surge of weeds. This suppression was further complemented by the subsequent post-emergence application of tembotrione, which potentially managed the subsequent wave of weeds. As a result, this combined approach led to enhanced weed control across all the different tillage practices. These findings suggest that alongside the application of pre-emergence herbicides (atrazine or pendimethalin), the inclusion of tembotrione at a rate of 120 g/ha could potentially enhance the efficiency of weed control for the crops.

Maize yield attribute and yield: The yield and yield attributes of maize crop differed significantly due to tillage and weed-control measures. The highest grain yield of maize was achieved with ZT-M+BM (M4) applied plot (6.72 t/ha), 17.7% increase in grain yield compared to CT-M (5.53 t/ha). Additionally, the weed-free check plot exhibited a 25.43% increase in grain yield compared to the un-weedy check plot., which remained notably higher than other weed manage-

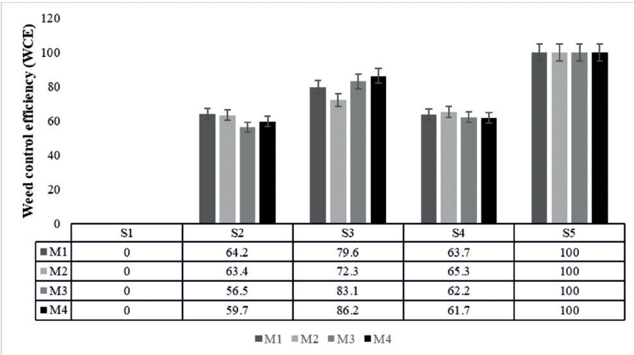


Fig. 3. Effect of crop establishment methods and weed management on Weed control efficiency (WCE) at 60 DAS

M1: CT -Maize; M2: CT-Maize + Green manure; M3: ZT-Maize + Residue*; M4: ZT-Maize + Sesbania Brown manure; S1: Un-weeded check ; S2: Pre (atrazine +pendimethaline @ 750g/ha) +1 HW at 25 DAS; S3: Pre (atrazine +pendimethaline @ 750g/ha) + Post (tembotrione @120g/ha); S4: Pre (atrazine +pendimethaline @ 750g/ha) + Post (Premix mesotrione+atrazine @120g/ha) § ; S5: Weed free check.

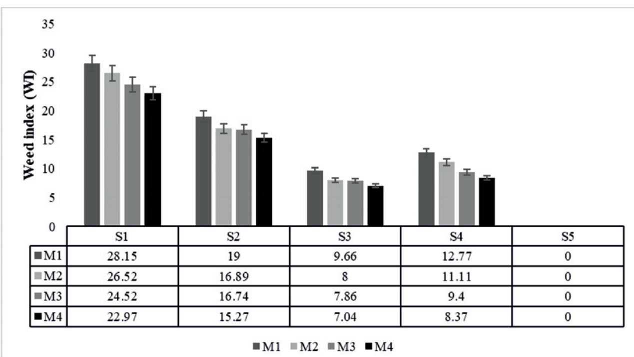


Fig. 4. Effect of crop establishment methods and weed management on Weed index (WI)

M1: CT -Maize; M2: CT-Maize + Green manure; M3: ZT-Maize + Residue*; M4: ZT-Maize + Sesbania Brown manure; S1: Un-weeded check; S2: Pre (atrazine +pendimethaline @ 750g/ha) +1 HW at 25 DAS; S3: Pre (atrazine +pendimethaline @ 750g/ha) + Post (tembotrione @120g/ha); S4: Pre (atrazine +pendimethaline @ 750g/ha) + Post (Premix mesotrione+atrazine @120g/ha) § ; S5: Weed free check.

ment methods (Figure:5). ZT-M+BM (M4) demonstrated higher values for cobs length, cob girth, cob weight, shelling percentage, number of grains per cob, and 100 grain weight. On the other hand, the M1: CT-M plot showed the lowest values for these yield attributes (Table:3). The ZT-maize with *Sesbania* brown manuring also exhibited the highest total biological yield, surpassing CT-maize. Additionally, the ZT+BM treatment yielded the higher straw yield. The weed-free treatment (WFC) resulted in significantly higher values for cob length, cob girth, cob weight, shelling percentage, number of kernel rows per cob, number of kernels per row, and 100-grain weight at harvest (Table:3). These results were comparable to the Pre + Post (Tembotrione) and Pre + Post (Premix Meso+Atra) treatments. The treatment receiving sequential application of atrazine @ 750 g/ha with pendimethalin @ 750 g/ha (pre) *fb*. tembotrione at 120 g/ha as post-emergence recorded significantly higher grain yields (6.32 t/ha) after WFC (Figure:5).

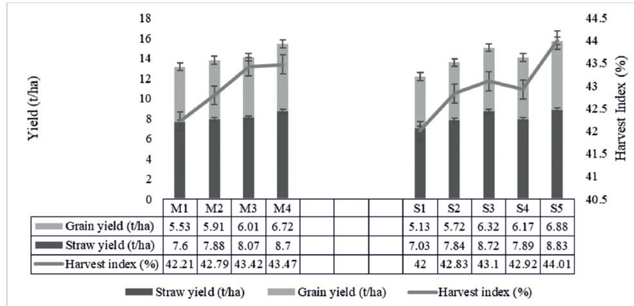


Fig. 5. Effect of crop establishment methods and weed management on total biomass, grain yield, total straw yield and harvest index

M1: CT-Maize; M2: CT-Maize + Green manure; M3: ZT-Maize + Residue*; M4: ZT-Maize + Sesbania Brown manure; S1: Un-weeded check; S2: Pre (atrazine +pendimethaline @ 750g/ha) +1 HW at 25 DAS; S3: Pre (atrazine +pendimethaline @ 750g/ha) + Post (tembotrione @120g/ha); S4: Pre (atrazine +pendimethaline @ 750g/ha) + Post (Premix mesotrione+atrazine @120g/ha) § ; S5: Weed free check.

Gupta *et al*. (2018) observed that the highest stover yield in hybrid maize was attained through a pre-emergence treatment involving a combination of atrazine 50 WP and pendimethalin 30 EC, each applied @ 750 g/ha, within 24 hours of sowing. With the pre-emergence application of atrazine 50 WP @ 1.0 kg/ha after 24 hours of sowing, it was followed by a sequential post-emergence application of tembotrione 34.4 SC @120 g/ha on 25 DAS. The stover yield obtained under this treatment remained at par with two hand weeding done on 20 and 40 DAS. Similarly, Sharma *et al*. (2018) revealed that significantly higher grain and stover yields for maize were recorded under no tillage conditions, surpassing outcomes from conventional tillage methods.

Among the weed management methods, S5 (weed-free check) achieved the highest net returns at 112,320/ha followed by S3 (Pre + Post Tembotrione) at 109,230/ha, and S2 (Pre + 1 HW at 30 DAS) at 97,730/ha. In contrast, W1 (un-weeded check) yielded net returns of 77,530/ha. Although the weedy check had the lowest cultivation costs, it resulted in the lowest returns due to reduced yields. In terms of net returns, ZT-Maize + Sesbania Brown manure (M4) performed the best, with a value of 116,570/ha, followed by CT-Maize with 94,320/ha. Among the crop establishment methods, ZT-maize with Sesbania brown manuring (M4) achieved the highest net benefit-cost (B:C) ratio of 3.71, surpassing other methods. For weed management, the Pre+Post (Tembotrione) (S3) option had the highest net B:C ratio of 3.01, outperforming other options (Table:3). The superior B:C ratios for ZT-maize with Sesbania brown manuring and Pre+Post (Tembotrione)

Table 3. Effect of crop establishment methods and weed management on cob length (cm), cob girth (cm), cob weight (g), shelling %, kernel no/cob, Kernel row/cob, Kernel weight/cob, Seed index and economics of maize at harvest (Two years pooled data).

Treatment	Cob length (cm)	Cob girth (cm)	Cob weight (g)	Shelling %	Karnel row/ cob	Kernel No./ row	Kernel weight/ cob (g)	Seed index (g)	B:C ratio
Crop establishment methods									
CT-Maize	13.3	12.7	117.7	72.0	11.7	27.0	83.8	22.8	2.70
CT-Maize + Green manure	13.4	12.9	119.5	73.6	12.3	27.0	86.8	23.0	2.26
ZT-Maize + Residue*	14.6	13.7	123.9	76.0	12.5	28.8	88.0	23.8	2.38
ZT-Maize + *Sesbania* BM	16.1	15.8	130.1	81.6	13.4	29.9	98.5	24.5	3.71
SEm±	0.4	0.4	2.5	1.9	0.2	0.6	2.0	0.4	-
CD (P=0.05)	1.4	1.2	8.6	6.5	0.5	2.1	7.1	1.2	-
Weed management options									
Un-weeded check	11.5	12.0	110.3	69.2	10.9	25.9	75.8	22.0	2.43
Pre +1 HW	13.7	13.1	119.2	71.6	11.7	26.4	81.8	21.8	2.70
Pre + Post (*Tembotrione)*	15.4	14.6	126.5	80.6	13.2	29.4	96.9	24.2	3.01
Pre + Post (Premix *Meso+Atra*) §	14.8	13.9	122.5	70.1	12.5	27.9	82.3	23.2	2.73
Weed free check	16.5	15.4	135.6	87.3	14.1	31.9	109.5	26.4	2.65
SEm±	0.4	0.4	3.6	2.2	0.3	0.8	2.1	0.5	-
CD (P=0.05)	1.1	1.3	10.5	6.3	0.7	2.2	6.1	1.5	-

Note: CT, conventional tillage; ZT, zero tillage; *wheat residue @ 3t/ha; PRE, pre-emergence (atrazine + pendimethaline @ 750 g/ha each); POST, post-emergence; HW, hand weeding at 25 DAS; Tembo, tembotrione @ 120 g/ha; §:pre-mix dose, mesotrione + atrazine @ 120 g/ha. BM: Brown manuring (*Sesbania*)

were due to their higher yields and lower cultivation costs.

Correlation coefficient analysis between weed density (no/m^2) and grain yield (t/ha) in maize: The graph showing the corelation between the weed density (no/m^2) and grain yield (t/ha) of maize at 60 DAS. A negative linear correlation between weed density and yield in maize crop suggests that as the density of weeds increases, the yield of maize decreases in a linear manner. This suggests that increasing the number of weeds has a detrimental impact on the growth and productivity of maize, because weeds compete with the maize crop for essential resources such as water, nutrients, and sunlight. As weed density increases, they consume a larger share of these resources, leaving fewer available for the maize plants. This competition can lead to reduced growth, lower photosynthesis rates, and ultimately, a decrease in the yield of maize. We found the R^2 value 0.86 (Figure:6). It clearly suggested that weed biomass accounted for 86% variation in grain yield. The outcome is backed by the research conducted by Mitra *et al.* in 2018.

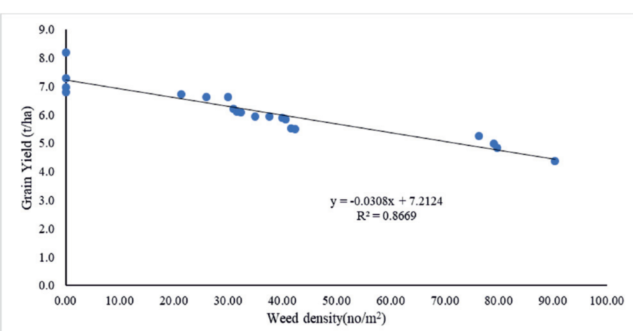


Fig. 6. Correlation between weed density (no/m^2) and grain yield (t/ha) of maize

Microbial biomass carbon and fluorescein diacetate hydrolysis activity: Microbial biomass carbon (MBC) and fluorescein diacetate (FDA) serve as indicators of microbial activity, and these parameters showed significant variations based on different crop establishment methods and weed management options. At the flowering stage of maize, MBC was highest under M4: ZT-maize with *Sesbania* co-culture as brown manure (156.01 µg/g soil), surpassing all other treatments. Similarly, FDA at the flowering stage of maize was also notably higher under (M4): ZT-maize with Sesbania co-culture as brown manure (133.78 µg/g soil) compared to other establishment methods. Among the different weed management options, MBC at the flowering stage was highest in the weed-free check (148.65 µg/g soil), outperforming the other treatments. For maize, FDA at the flowering stage was also higher in the (S3) Pre+ Post (Tembotrione) plot (116.27 µg/g soil), although not statistically significant compared to the un-weeded check (Figure:7).

The increased microbial activity in the ZT-maize treatment, both with brown manure and residue retention, likely contributed to the higher MBC in the soil. Overall, the combination of organic matter accumulation, reduced soil disturbance, moisture conservation, carbon sequestration, and nutrient retention in ZT systems provides an advantageous environment for soil microorganisms, resulting in higher microbial biomass carbon compared to conventional

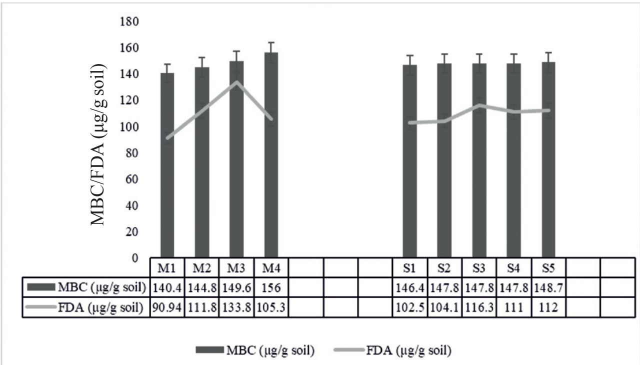


Fig. 7. Effect of crop establishment methods and weed management on microbial biomass carbon (MBC) and fluorescein diacetate hydrolysis activity (FDA) at flowering in maize.
M1: CT-Maize; M2: CT-Maize + Green manure; M3: ZT-Maize + Residue*; M4: ZT-Maize + *Sesbania* Brown manure; S1: Un-weeded check; S2: Pre (atrazine +pendimethaline @ 750g/ha) +1 HW at 25 DAS; S3: Pre (atrazine +pendimethaline @ 750g/ha) + Post (*tembotrione* @120g/ha); S4: Pre (atrazine +pendimethaline @ 750g/ha) + Post (Premix *mesotrione+atrazine* @120g/ha) § ; S5: Weed free check.

tillage practices (Sturz and Christie, 2003). Zero tillage involves minimal soil disturbance compared to conventional tillage (CT) methods. This preservation of soil structure and the undisturbed environment create favourable conditions for soil microorganisms to thrive. The reduced disturbance allows the microbes to establish and multiply, leading to higher FDA activity. In ZT systems, crop residues are left on the soil surface, providing a continuous source of organic matter. The presence of these residues enhances microbial activity, as they serve as a readily available food source for soil microorganisms. More organic matter leads to higher microbial activity, which is reflected in the increased FDA levels. Moreover, root nodulation in *Sesbania* brown manure leads to increased rhizodeposition/bioturbation, creating a tilled layer within the soil depths, which could explain the larger microbial population in the brown manure (Roldan *et al*., 2003).

Thus, for effective weed control and achieving high maize productivity ZT with brown manure, alongside the sequential application of atrazine @ 750g/ha with pendimethalin @ 750 g/ha (pre-emergence), and tembotrione (34.4 EC) @ 120 g/ha may be recommended in the Indo-Gangetic plains of India.

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