JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(10), 126–143
https://doi.org/10.12911/22998993/205713
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Received: 2025.05.20
Accepted: 2025.07.15
Published: 2025.07.22

Ecological insights into weed seed bank dynamics: Management strategies through tillage and mulching interventions in maize (*Zea mays* L.) fields

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ABSTRACT

Weed management is crucial for maize production, as weeds compete for resources and reduce yields. Understanding the weed seed bank dynamics and integrating effective practices like tillage and mulching can help control weeds as well as improve crop productivity. A field study was piloted in 2017 and 2018 at the Agronomic Research Area, University of Agriculture Faisalabad, Pakistan, to assess the impact of different tillage practices: zero tillage (T_1), cultivator twice with planking (T_2), moldboard plough with cultivator twice and planking (T_3), and chisel plough with cultivator twice and planking (T_4) and mulching practices: no mulch = M_1, plastic mulch = M_2, and straw mulch (sorghum straw at 5 t/ha = M_3) on the weed seed bank dynamics, weeds growth and maize productivity. The results revealed that chisel plough and polythene mulch significantly reduced weed density (28.5% and 73.1%, respectively) and biomass (67.1% and 92.1% in fresh biomass, and 62.2% and 91.4% in dry biomass, respectively). MB plough and polythene mulch reduced weed seed density by 39.6% and 48.7% at 0–5 cm depth, respectively. Chisel plough and straw mulch augmented grain yield by 45% and 6% compared, respectively, to zero tillage and no mulching. The combination of chisel plough and straw mulch generated the maximum net income (US$719/ha) and benefit cost ratio (1.82), with a 146.5% increase compared to the control treatment. In crux, chisel ploughing combined with straw mulching is a promising approach for sustainable maize production, offering improved weed control, increased grain yield, and enhanced economic returns.

Keywords: economic viability, mulching, productivity, tillage, weed prevalence, weed seed bank dynamics.

INTRODUCTION

Maize (*Zea mays* L.) is a worldwide substantial crop, ranking 3rd among cereals with respect to cultivated area (Shahzad et al., 2017; FAO, 2019). In Pakistan, maize is cultivated on 1.41 million hectares, producing 8.46 million tons of grain and paying 0.5% to the country's GDP (GOP, 2024). Maize productivity is significantly affected by both abiotic and biotic variables, involving weeds (Farooq et al., 2017). Weeds are considered as the foremost threat in farming, competing with crops for resources as well as reducing yield and quality (Maqsood et al., 2020; Ameena et al., 2024).

Weed management is essential for achieving ecological magnification in agriculture, and current reliance on chemical approaches is being reevaluated owing to societal pressure to lessen synthetic herbicide usage (Chikowo et al., 2009; Petit et al., 2015). The improvement of sustainable weed management approaches is essential to mitigate the negative effects of weeds on crop production. Weed seed banks in soil represent a significant source of future weed infestation, and their management is critical for sustainable agriculture (Shrestha et al., 2002; Chauhan and Johnson, 2010). The composition and size of the weed seed bank are governed by various factors, including tillage systems, crop rotation, and weed management strategies (Baraibar et al., 2009). Understanding the dynamics of weed seeds banks is vital for evolving operative weed management approaches.

Tillage, an essential agricultural practice, encompasses mechanical operation of soil for seedbed preparation, governing weeds, and managing crop residues (Hobbs et al., 2008). Different tillage systems, such as conservation tillage, conventional tillage, and zero tillage, can affect weed seed bank dynamics and crop yields (Scherner et al., 2016). Reduced and conservation tillage can cause increased weed abundance and community shifts (Derrouch et al., 2021; Scherner et al., 2016), while deep tillage can bury weed seeds, reducing their germination and emergence (Mohler et al., 1993). Tillage effect on weed seedbank can vary, depending on the kind of tillage, soil category, and crop rotation. Mulching is another essential practice that can improve soil moisture, subdue weeds, and normalize soil temperature (Maqsood et al., 2020). Diverse mulch resources, such as organic mulches (e.g., wood or straw chips), plastic mulches, and biodegradable mulches, can be used to achieve these benefits (Abed Gatea Al-Shammary et al., 2020; Yang et al., 2020). Plastic mulching, in particular, can have a key role in crop growth and development by conserving soil moistness and decreasing weed invasion (Briassoulis et al., 2018; Akhir et al., 2022). Additionally, soil solarization involving a clear plastic sheet can trap radiations, raising soil temperature and controlling weeds (Lee and Christian, 2017).

The optimal integration of tillage and mulching strategies for maximizing maize yields and economics remains unclear. Previous studies have presented that the amalgamation of tillage and mulching could synergistically impact weeds and yield (Scherner et al., 2016; Maqsood et al., 2018). However, the specific outcomes of various mulching practices and tillage systems on weed seeds bank, weed prevalence, and maize productivity need to be further investigated. This study aimed to bridge the knowledge gap by evaluating various tillage methods and mulching techniques to identify the most effective combination for sustainable maize production. It was hypothesized that the combination of deep tillage and mulching would significantly reduce weed pressure and enhance maize yields under semiarid conditions, outperforming shallow tillage practices without mulching. By exploring the synergistic effects of these practices, this study sought to provide new insights into sustainable agricultural practices for managing weeds as well as improving crop yields and resource use efficiency under semiarid conditions. The outcomes of this study will add to the improvement of efficient and sustainable weed control measures for maize production.

MATERIALS AND METHODS

Study site and weather conditions

Experimentation was carried out for two consecutive years during kharif (July sown) of 2017 and 2018 at Agronomy Experimental Area, University of Agriculture, Faisalabad, Pakistan (73.05 °E longitude, 31.3 °N latitude, 184 m height). Soil sampling was done with the help of soil auger from two different soil profiles (0–15 cm and 15–30 cm). Ishaq et al. (2002) outlined standard procedures were followed for determining the physico-chemical characteristics of soil, which were governed by analyzing composite soil samples (Table 1). The soil was characterized as

Table 1. Soil physicochemical parameters

Characteristics	2017		2018		Units	Status
	0–15 cm	15–30 cm	0–15 cm	15–30 cm		
Texture	Sandy clay loam					
pH	7.84	7.69	7.78	7.66		Medium alkaline
Electrical conductivity (EC)	1.47	1.58	1.32	1.52	dS m^{-1}	Non-saline
Exchangeable sodium (Na)	0.48	0.49	0.43	0.28	mmol 100 g^{-1}	Normal
Total nitrogen (N)	0.051	0.038	0.055	0.044	%	Low
Available phosphorus (P)	7.81	5.75	21.05	16.09	mg kg^{-1}	Low
Exchangeable potassium (K)	149	127	213	184	mg kg^{-1}	Medium
Organic matter	0.94	0.76	0.84	0.63	%	Low
Bulk density	1.43	1.47	1.51	1.56	mg m^{-3}	

Hafizabad series (fine-loamy, mixed, hyperthermic, Typic Calciargids) with a sandy clay loam texture as stated by the USDA soil taxonomy. The meteorological conditions data for the 2017 and 2018 crop seasons were obtained from a meteorological observatory (Crop Physiology section, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan) located roughly 1.5 km from the trial site (Figure 1).

Experimental design and treatments

The study employed a randomized complete block design (RCBD) with a split-plot arrangement in triplicate. Main plots consisted of four tillage practices: zero tillage (T_1, control), cultivator 2 times + planking 1 time (T_2), cultivator 2 times + moldboard plough 1 time + planking 1 time (T_3), and cultivator 2 times + chisel plough 1 time + planking 1 time (T_4). Subplots comprised three mulching treatments: M_1 = no mulch as a control treatment, M_2 = plastic mulch (300 cm wide, 8 µm thick), and M_3 = sorghum straw mulch (applied at a rate of 5 tons ha^{-1}). The tillage treatments employed in this research are outlined in Table 2, which provides a comprehensive explanation of the specific methodologies used.

Crop management

The crop rotation followed in this study was Fallow-Maize-Wheat-Maize. Each year, the field was prepared with pre-sowing irrigation (Rauni) to achieve optimal moisture levels. Tillage operations were performed according to treatment requirements, followed by planking. Maize hybrid DK-6714 was manually sown on July 15th and 17th in 2017 and 2018, correspondingly, using a seed drill (hand driven) to maintain R×R (75 cm) and P×P (25 cm) spacing by thinning after 10 days after sowing. The seeding rate was kept 25 kg ha^{-1}. Urea, diammonium phosphate (DAP), and potassium sulfate (SOP) were used as fertilizers (NPK) sources and applied at rates of 250 kg N ha^{-1}, 150 kg P ha^{-1}, and 125 kg K ha^{-1}, respectively.

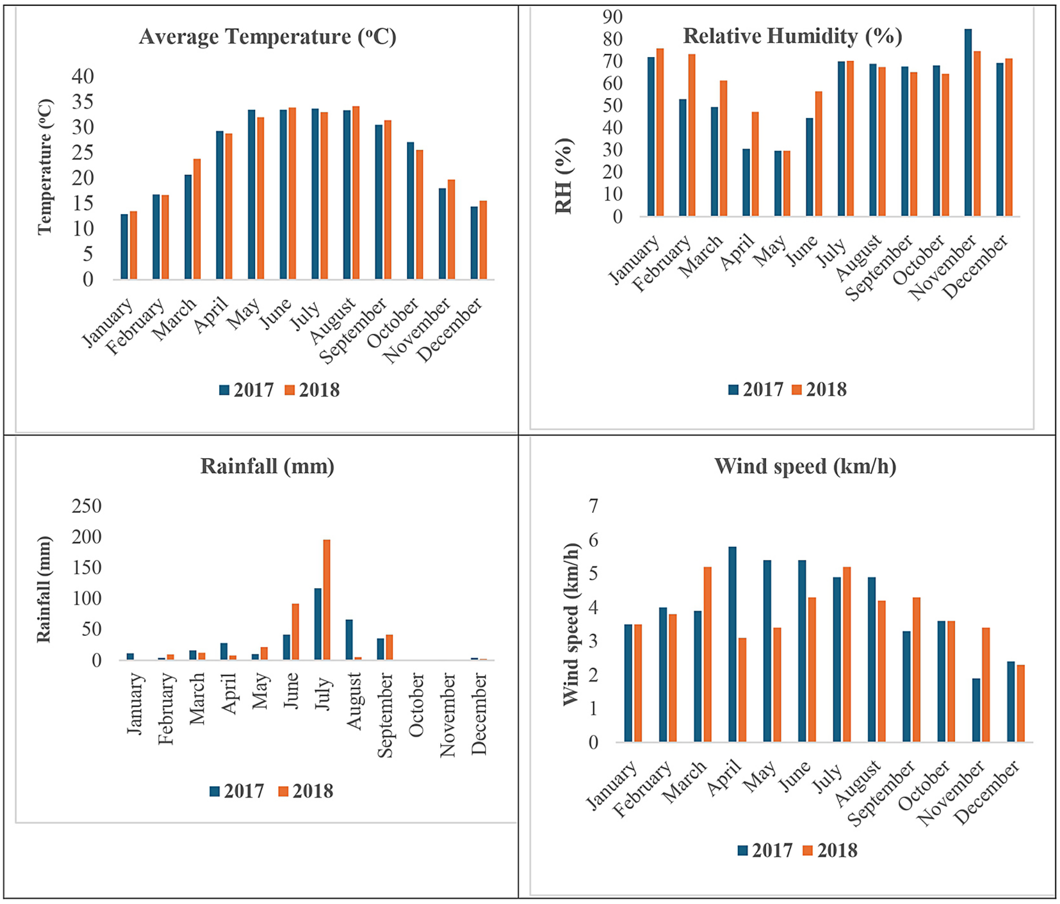

Figure 1. Climatic conditions of experimental site during 2017 and 2018: average temperature (oC), relative humidity (%), rainfall (mm) and wind speed (km/h).

Table 2. Description of the tillage treatments, equipment used, the level of soil disturbance

Treatment		Equipment/tools used	Cultivation depth and the level of soil disturbance
T_1	Zero tillage (Control)	Hand driven seed drill	Sowing was carried out in shallow furrows (3–5 cm) with localized soil disturbance along the furrow
T_2	Cultivator 2 times + Planking 1 time	Cultivator, Planker and hand driven seed drill	Primary tillage involved soil loosening to a depth of 18–20 cm. Subsequent soil preparation utilized a flat wooden Plank to level and smooth the soil surface, creating a uniform seedbed. Sowing was then carried out in shallow furrows (3–5 cm deep)
T_3	Cultivator 2 times + Moldboard plough 1 time + Planking 1 time	Cultivator, Moldboard plough, Planker and hand driven seed drill	The primary tillage operation loosened and aerated the soil to 18–20 cm depth, while subsequent seedbed preparation involved shallow soil mixing to 10–12 cm depth. A flat wooden tool was employed to even out and refine the soil surface after tilling, ensuring a uniform seedbed. Sowing was then carried out in shallow furrows (3–5 cm deep)
T_4	Cultivator 2 times + Chisel plough 1 time + Planking 1 time	Cultivator, Chisel plough, Planker and hand driven seed drill	Primary tillage involved deep soil loosening and aeration to 18–20 cm, followed by seedbed preparation that entailed deep soil loosening (30–35 cm) without inversion. A wooden leveling tool was then used to smooth and refine the soil surface, creating a uniform seedbed for sowing in shallow furrows (3–5 cm deep)

The whole amount of phosphorus and potassium were given as a basal dose, whereas nitrogen was divided into three applications: one-third at the time of sowing, one-third at the third leaf collar stage, and one-third at the fourth leaf collar stage. For plastic mulching, transparent polythene strips were cut to size and placed between rows, secured with soil. Straw mulch was used at 5 t ha^{-1} after chopping sorghum stalks with an electric chopper.

The crop received eight irrigations, with the first irrigation 10 days after sowing. Subsequent irrigations were scheduled based on critical growth stages. Plant spacing was maintained by thinning at 4th leaf stage. Hand weeding was performed after recording weed data to keep the field weed-free. Carbofuran (Furadan 3G) was applied at 20 kg ha^{-1} to control shoot fly and maize borer.

Observation and data recording

Weeds seed bank sampling

Soil sampling was done from 0–30 cm soil profiles using a soil auger with an internal diameter of 8.86 cm before sowing and after harvesting (Cardina et al., 1991). From the trial field, 1m x 1m plots were randomly chosen for soil core sampling at varying depths (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, and 25–30 cm) prior to the experiment initiation in both 2017 and 2018. A total of 36 soil samples was prepared for assessing the weed seeds bank. Soil core samples were collected from random points within 1 m^2 quadrats in each treatment, across three replicates, to ensure representative sampling. Samples were taken at six depth intervals (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, and 25–30 cm) at the autumn harvest of maize in 2017 and 2018. This sampling effort yielded 216 soil samples for the analysis of weed seeds bank. The collected samples were carefully carried in craft paper bags to the field research laboratory and kept in cooled chambers (at 4 °C) to maintain seed viability. A germination trial was conducted to estimate the viable non-dormant seed population (Clements et al., 1996). Soil samples were placed in 3 cm deep containers and soaked to sustain moisture levels sufficient for germination. The containers were observed for four months, and plantlets were recognized by species, then calculated, and pulled out once documented. Soil stirring was done once a month to facilitate germination and prevent plant competition (Benoit et al., 1991). The trays were re-watered after one week to obtain better germination.

After the germination trial, the remaining soil was rinsed with water through fine nylon sieves to extract seeds (Forcella et al., 2004). A sieve with an opening size of 2.36 mm was used for sieving of samples to remove organic materials, clods, stones, straws and leaves. The samples were carefully inspected to ensure no seeds were lost. The seeds were then separated from the minute sand particles by passing the samples through a sieve with a 500 μm (# 35) mesh size. The twisted samples with seeds and seed-like components underwent an overnight oven drying process at 42 °C. Seeds were carefully removed using a magnifying glass and categorized by species (Fogliatti, 2003). Weed seed density was estimated by using the following formula:

$$Total\ weed\ seed\ density\ = \tag{1}$$
$$= \frac{Total\ no. of\ seeds\ of\ all\ individuals\ collected}{\text{Total area}}$$

Relative abundance represents the proportion of seeds of a particular species within the entire weed community per unit area (Caamal-Maldonado et al., 2001). It was estimated by using the following formula:

$$Relative\ abundance\ (\%) = \tag{2}$$
$$= \frac{Total\ No. of\ weed\ seeds\ of\ a\ species}{Total\ No. of\ weed\ seeds} \times 100$$

Weed density

Weed density was determined by manually counting weeds within a 0.5 m² quadrat located twice in each plot. Weeds were removed to facilitate data collection. Fresh weight was measured by harvesting weeds, placing them in plastic bags, and weighing them on an electronic balance in the laboratory. The weeds were oven-dried at 72 °C for three days in craft paper bags. After drying, the bags were weighed again to calculate dry weight.

Crop harvesting and yield assessment

The maize crop was harvested (manually) on November 10th and 15th in 2017 and 2018, respectively, and left in the plots for one week to dry naturally. For measuring plant height, a meter rod was used and averaged from five indiscriminately selected plants. Grain yield was calculated by bulking threshed, cleaned, and air-dried maize grains, ensuring a moisture level of 14%. To calculate the 1000-grain weight, a precise counting process was employed to select exactly 1000 grains, which were subsequently weighed using a high-precision electronic scale. Biological yield was assessed by weighing dried crop bundles with a spring balance. The following equation was used for harvest index measurement as the ratio of economic yield (grain yield) to biological yield, expressed as a percentage.

$$Harvest\ index\ (\%) = \tag{3}$$
$$= \frac{Economic\ yield\ (grain\ yield)}{Biological\ yield} \times 100$$

Economic analysis

The economic analysis followed the guidelines of the CIMMYT (CIMMYT, 1998). Costs were categorized into fixed costs (seed, irrigation, fertilizers, crop protection, harvesting, and management) and variable costs (tillage and mulching). The economic performance was evaluated by quantifying the revenue generated from grain and straw sales. Profitability was assessed by deducting overall costs from revenue. A cost-benefit analysis was conducted using a ratio that compared revenue to total expenses, providing insight into the economic viability of the endeavor.

Statistical analysis

Data was statistically analyzed by using the Statistix software to evaluate treatment effects. Significant differences were assessed by performing Analysis of variance (ANOVA). Means were separated by using Tukey's Honest Significant Difference (HSD) test at $p \leq 0.05$ significance level. Data visualization was done using SigmaPlot software to create graphical representations. These visualizations helped illustrate significant differences between treatment groups.

RESULTS

Climatic conditions

The summer seasons of 2017 and 2018 exhibited distinct climatic conditions. Temperature and rainfall patterns differed significantly between the two years. In 2017, the mean minimum temperature was 16 °C, whereas in 2018, it was 17.8 °C. Conversely, the mean maximum temperature was higher in 2017 (39.5 °C) compared to 2018 (38.8 °C). Rainfall distribution also varied, with 2018 receiving more total rainfall (286 mm) than 2017 (260 mm). However, the events of rainy days (during the crop growth period) were higher in 2017 (24 days) than in 2018 (19 days). Notably, the rainfall patterns during specific months, such as September and October, differed between the two years, potentially influencing the grain filling period (Figure 1). These climatic variations may have differentially impacted maize performance, as well as the growth and competitiveness of persistent weeds.

Weeds prevalence

Soil analysis for weed seeds bank revealed a heterogeneous distribution and density of weed seeds across different soil profiles. The seed bank comprised 15 weed species, including Horse Purslane (*Trianthema portulacastrum* L.), False Amaranth (*Digera muricata*), Purple Nutsedge (*Cyperus rotundus*), Slender Amaranth (*Amaranthus viridis*), Bermuda Grass (*Cynodon dactylon* L.), Johnson Grass (*Sorghum halepense* L.), Sweet Clover (*Melilotus indica*), Barnyard Grass (*Echinochloa crus-galli* L.), Purslane (*Portulaca oleracea* L.), Lambsquarter (*Chenopodium album*), Broadleaf Dock (*Rumex obtusifolius*), Jungle Rice (*Echinochloa colona* L.), Swine Cress (*Coronopus didymus*), Field Bindweed (*Convolvulus arvensis*), and Lesser Jack (*Emex spinosa*) (Figure 2). These species exhibited varying densities across various soil profiles.

Weed seed density (seeds m^{-2})

The soil samples collected before sowing in 2017 (Figure 3a) and 2018 (Figure 4) revealed varying weed seeds densities at various depths. In 2017, the highest weed seed density was observed in the top 0–5 cm soil layer, ranging from 12,314 to 15,414 seeds m^{-2}, followed by 5–10 cm. In 2018, the maximum weed seeds bank was also observed in the topmost soil layer 0–5 cm, ranging from 8.773 to 16.137 seeds m^{-2}. The weed seeds density declined with increasing soil depth, with the lowest density observed at 25–30 cm depth, ranging from 4904 seeds m^{-2} in 2017 and 4695 seeds m^{-2} in 2018. These results indicate that the maximum weed seeds bank was concentrated in top layer, with decreasing density at greater depths. The initial weed seed density before sowing provides a baseline for evaluating the effects of tillage systems and mulching practices on weed seed density during the crop growing season.

In contrast, mulching practices had varying effects on weed seed density between 2017 and 2018. At 0–5 cm depth, polythene mulch (M_2) significantly reduced weed seed density by 17.7% in 2017 and 48.7% in 2018, compared to no mulching (M_1). At deeper soil depths, polythene mulch (M_2) consistently reduced weed seed density, with significant reductions observed at 15–20 cm depth in 2018. Specifically, polythene mulch (M_2) reduced weed seed density by 36.5% at 15–20 cm depth in 2018 (Figure 4).

The interactive effect of tillage systems and mulching practices on weed seed density was non-significant at all soil depths in both years. However, the results suggest that MB plough and

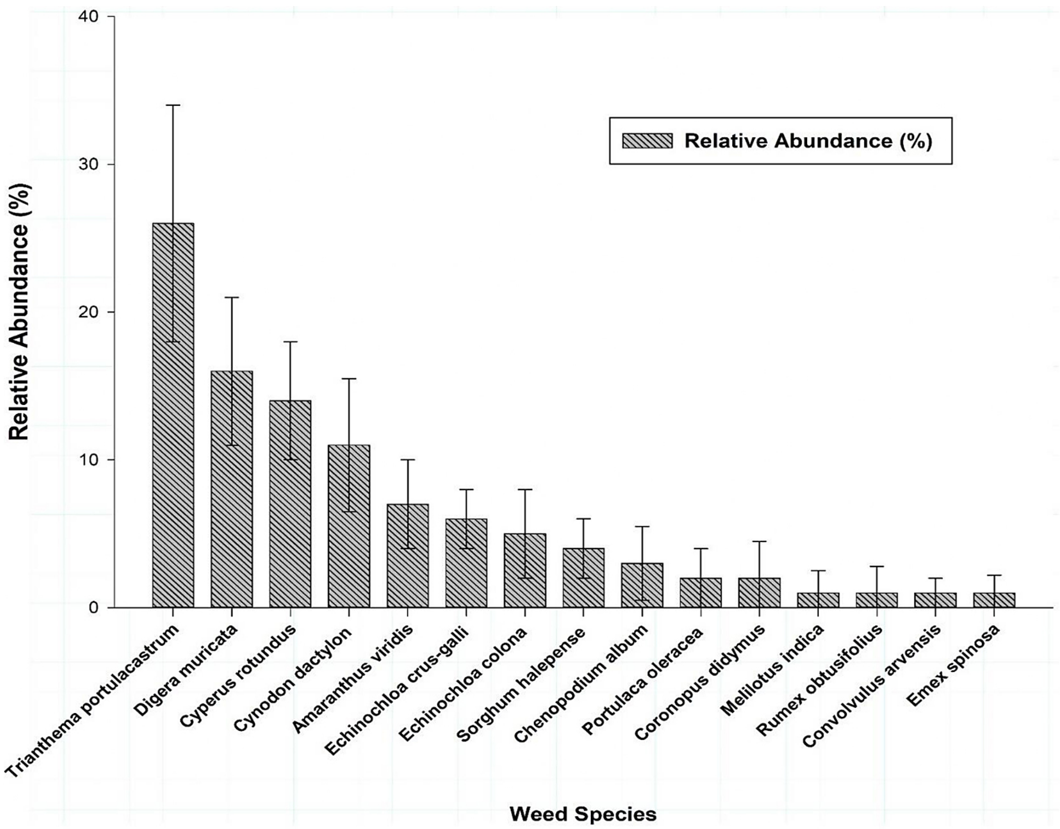

Figure 2. Relative abundance (%) of weeds seeds in soil weed seed bank recorded during 2017–2018

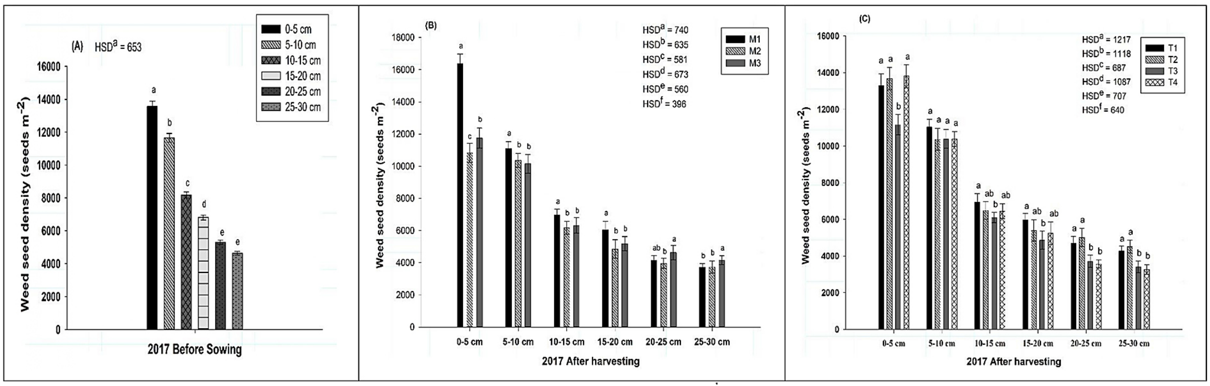

Figure 3. Impact of various tillage systems and mulching practices on weed seed density (seeds·m^{-2}) before sowing (A) and after sowing (B & C) in different soil profiles during 2017: HSD – Honestly significant difference; HSDa – HSD value for 0–5 cm depth; HSDb – HSD value for 5–10 cm depth; HSDc – HSD value for 10–15 cm depth; HSD < l – HSD value for 15–20 cm depth; HSDe – HSD value for 20–25 cm depth; HSDf – HSD value for 25–30 cm depth; T1 – Zero tillage; T2 – Cultivator 2 times + planking l time; T3 – Cultivator 2 times + MB Plough l time + planking l time; T4 – Cultivator 2 times + Chisel plough l time + planking l time; M1 – No mulch; M2 – Plastic mulch (300 cm wide; 8 µm thick); M3 – Sorghum straw mulch at 5 tones·ha^{-1}; Bars (treatment mean ± standard error, n = 3) sharing different letters above the bar indicate significance at P ≤ 0.05 level within the same depth.

polythene mulch were effective in reducing weed seed density in various soil profiles, with varying degrees of effectiveness between 2017 and 2018. These findings have implications for the development of integrated weed management strategies that incorporate conservation tillage and mulching practices.

Presence of weed species and relative abundance (%)

The obtained results (Table 3) showed that the entire maize field was infested with these 15 weeds, either in the weed flora, weed seed bank, or both, during 2017 and 2018. Notably, nine species of weeds were found in both the weed seed bank and weeds flora, whereas six were only found in the soil weed seed bank. Among the nine species present in both, six (*Trianthema portulacastrum* L. *Cyperus rotundus*, *Digera muricata*, *Amaranthus viridis*, *Cynodon dactylon* L., and *Echinochloa crus-galli* L.) were the most abundant in the seed bank, with 100% presence in all experimental plots. In contrast, *Convolvulus arvensis* had the lowest presence (42%) in soil weed seed bank.

The relative abundance of weed species in the soil weed seed bank during 2017–18 is presented in Figure 4. The results indicate that the highest prevalent species was *Trianthema portulacastrum* L. accounting for 26% of the entire weed seed bank. Other abundant weed species included *Cyperus rotundus* (14%), *Digera muricata* (16%), *Amaranthus viridis* (7%), *Cynodon dactylon* L. (11%), and *Echinochloa crus-galli* L. (6%). In contrast, nine weed species were classified as minor weeds, each contributing ≤ 5% to the total relative abundance. These minor weeds included *Echinochloa colona*, *Sorghum halepense*, *Chenopodium album*, *Portulaca oleracea*, *Coronopus didymus*, *Melilotus indica*, *Rumex obtusifolius*, *Convolvulus arvensis*, and *Emex spinosa*.

Weed density (m^{-2}) and biomass

The impacts of tillage and mulching practices on weed density in maize fields were evaluated at 15 DAS, 30 DAS, and at harvest in 2017 and 2018 (Table 4). In 2017, the results showed that plots tilled with Chisel plough (T_4) had notably less weed density (189 m^{-2}) at 15 DAS, followed by MB plough (T_3) with 205.22 m^{-2} weed density. In contrast, zero tillage (T_1) and tine cultivator (T_2) had significantly higher weed densities (237.89 m^{-2} and 234.22 m^{-2}, respectively). Mulching practices also significantly reduced weed density, with polythene mulch (M_2) having the lowest weed density (126.69 m^{-2}) at 30 DAS. At harvest, tillage systems significantly affected the weed density, with the highest sum of weeds (272.07 m^{-2}) in zero tillage (T_1) and the lowest number (204.89 m^{-2}) in Chisel plough (T_4). Mulching practices also significantly

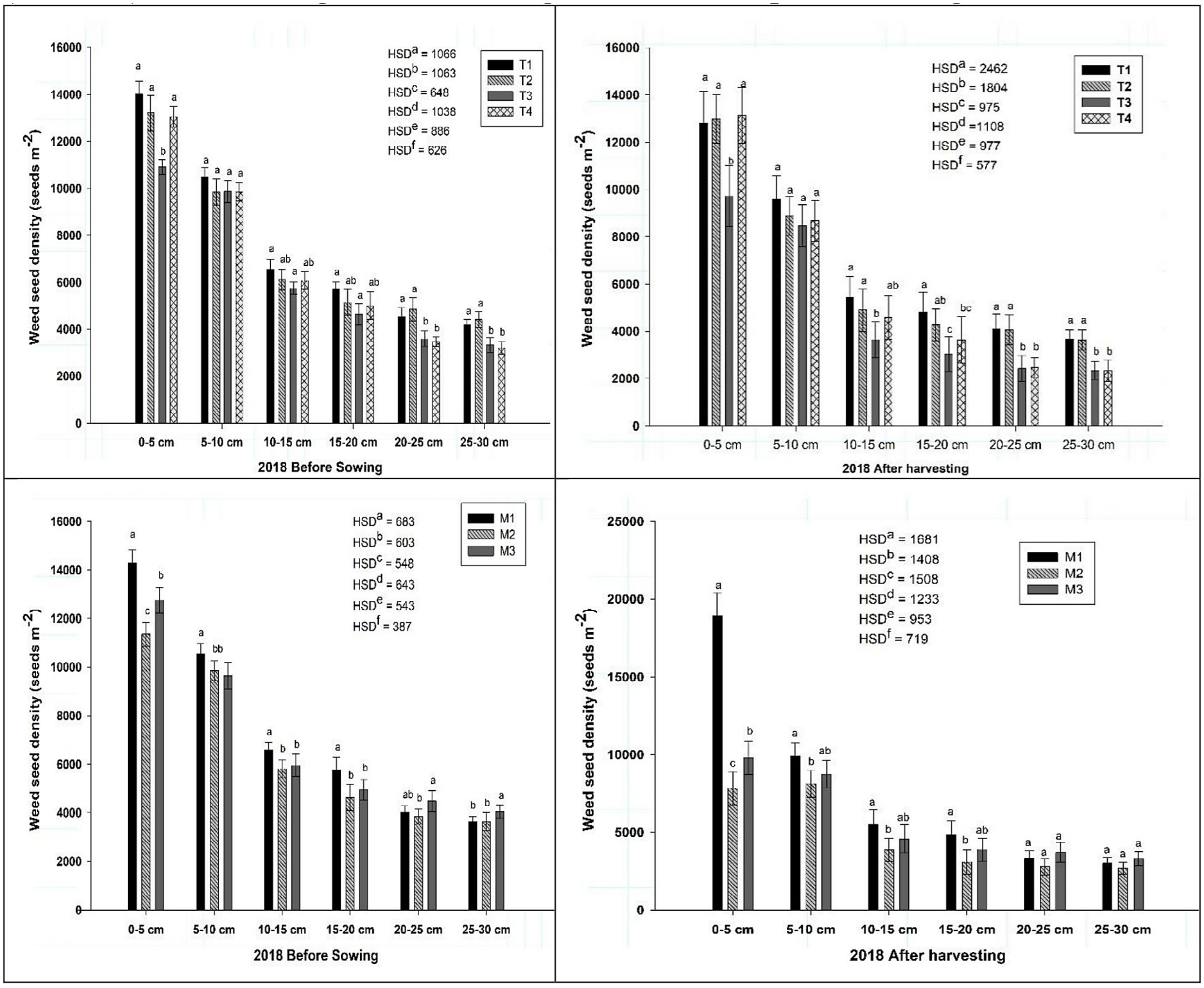

Figure 4. Impact of various tillage systems and mulching practices on weed seed density (seeds·m^{-2}) before sowing and after sowing in different soil profiles during 2018: HSD – Honestly significant difference; HSD3 – HSD value for 0–5 cm depth; HSDb – HSD value for 5–10 cm depth; HSDc – HSD value for 10–15 cm depth; HSDd – HSD value for 15–20 cm depth; HSDe – HSD value for 20–25 cm depth; HSDr – HSD value for 25–30 cm depth; T1 – Zero tillage; T2 – Cultivator 2 times + planking l time; T3 = Cultivator 2 times + MB Plough l time + planking l time; T4 – Cultivator 2 times + Chisel plough l time + planking l time; M1 – No mulch; M2= Plastic mulch (300 cm wide; 8 µm thick); M3 – Sorghum straw mulch at 5 tones·ha^{-1}; Bars (treatment mean ± standard error, n = 3) sharing different letters above the bar indicate significance at P ≤ 0.05 level within the same depth.

affected weed density, with polythene mulch (M_2) having the lowest weed density (24.75 m^{-2}). The significant interactive effect of tillage systems and mulching practices was noted, with Chisel plough × polythene mulch (T_4M_2) and MB plough × polythene mulch (T_3M_2) having lower weed densities (20.33 m^{-2} and 22.67 m^{-2}, respectively).

In 2018, the results showed that Chisel plough (T_4) had significantly less weed presence (166.78 m^{-2}) at 15 DAS, followed by MB plough (T_3) with 186.56 m^{-2} weed density. Zero tillage (T_1) had significantly higher weed density (218.67 m^{-2}). Mulching practices also significantly reduced weed density, with polythene mulch (M_2) having the lowest weed density (90.83 m^{-2}) at 15 DAS and 107.07 m^{-2} at 30 DAS. At harvest, Chisel plough (T_4) had significantly lower weed density (185.44 m^{-2}), while zero tillage (T_1) had the highest weed density (246.92 m^{-2}). Polythene mulch (M_2) significantly reduced weed density (90.83 m^{-2}) compared to no mulching (M_1) with 344.25 m^{-2}. Interactively, the tillage systems and mulching practices significantly affected the presence of weeds, with Chisel plough × polythene mulch (T_4M_2) having the lowest weed density (17.00 m^{-2}).

Tillage systems significantly affected the fresh biomass of weeds (Table 4), with Chisel

Table 3. Presence of weed species in soil seed bank and weed flora during experimentation

Weed species		Prevalence	
Common name	Scientific name	Soil seed bank	Weed flora
Horse purslane	*Trianthema portulacastrum* L.	✓	✓
Purple nutsedge	*Cyprus rutundus*	✓	✓
False amaranth	*Digra muricata*	✓	✓
Slender amaranth	*Amaranthus viridis*	✓	✓
Bermuda grass	*Cynodan dactylon* L.	✓	✓
Barnyard grass	*Echinochloa crus-galli* L.	✓	✓
Johnson grass	*Sorghum halepense* L.	✓	✗
Sweet Clover	*Melilotus indica*	✓	✗
Purslane	*Portulaca oleracea* L.	✓	✓
Jungle rice	*Echinochloa colona* L.	✓	✗
Lambs quarter	*Chenopodium album*	✓	✓
Broadleaf Dock	*Rumex obtusifolius*	✓	✓
Swine cress	*Coronopus didymus*	✓	✗
Field bind weed	*Convolvulus arvensis*	✓	✗
Lesser jack	*Emex spinosa*	✓	✗

Note: ✓= Presence in soil seed bank and weed flora; ✗ = Absence in soil seed bank and weed flora

plough (T_4) having the lowest fresh biomass of weeds (352.41 g m^{-2}), followed by MB plough (T_3) with 396.86 g m^{-2}. Mulching practices also significantly reduced the fresh biomass of weeds, with polythene mulch (M_2) having the lowest fresh biomass of weeds (42.57 g m^{-2}). With the significant interactive effect of tillage systems and mulching practices Chisel plough × polythene mulch (T_4M_2) and MB plough × polythene mulch (T_3M_2) was on par with each other in reducing weeds fresh biomass. In zero tillage (T_1), polythene mulch (M_2) significantly reduced the fresh biomass of weeds (51.03 g m^{-2}) compared to no mulching (M_1) with 1133.27 g m^{-2}. In 2018, tillage systems significantly affected the fresh biomass of weeds, with Chisel plough (T_4) having the lowest fresh biomass of weeds (314.88 g m^{-2}). Zero tillage (T_1) had significantly higher fresh biomass of weeds (419.27 g m^{-2}). Mulching practices also significantly reduced the fresh biomass of weeds, with polythene mulch (M_2) having the lowest fresh biomass of weeds (36.37 g m^{-2}). The interaction between tillage methods and mulching strategies was significant. Chisel plough × polythene mulch (T_4M_2) had the lowest fresh biomass of weeds (28.87 g m^{-2}), while zero tillage × no mulching (T_1M_1) had the highest fresh biomass of weeds (1031.2 g m^{-2}).

Similarly, tillage systems and mulching practices significantly affected the dry biomass of weeds, with Chisel plough (T_4) having the lowest dry biomass (52.86 g m^{-2} in 2017 and 48.46 g m^{-2} in 2018) and polythene mulch (M_2) being the most effective mulching treatment (5.60 g m^{-2}). The interactive effect of Chisel plough × polythene mulch (T_4M_2) lead to the least dry biomass (4.44 g m^{-2}) in 2018, while zero tillage × no mulching (T_1M_1) had the highest dry biomass (158.70 g m^{-2}).

Growth and yield components

The impact of tillage practices and mulching on maize growth and yield was evaluated (Table 5). Plant height was significantly influenced by tillage practices, with T_4 (Chisel plough + cultivator + planking) resulting in the tallest plants (241 cm and 248 cm in 2017 and 2018, respectively). This represented a 33% and 31% increase in plant height compared to T_1 (Zero tillage), which had plant heights of 180 cm and 189 cm in 2017 and 2018, respectively. Mulching practices also significantly affected plant height, with straw mulch (M_2) resulting in taller plants (216 cm and 227 cm in 2017 and 2018, respectively). This represented a 7% and 6% increase in plant height compared to the control treatment (M_1), which had plant heights of 201 cm and 213 cm in 2017 and 2018, respectively (Table 5).

Tillage and mulching practices significantly influenced maize yield and yield components.

Table 4. Impact of various tillage systems and mulching practices on weed density (m^{-2}) and weed growth in maize field during 2017 and 2018

Treatment	Weeds density at 15 DAS (m^{-2})		Weeds density at 30 DAS (m^{-2})		Weeds density at 15 harvesting (m^{-2})		Weeds fresh weight (g)		Weeds dry weight (g)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Tillage system (T)										
T_1	238^{a}	219^{a}	274^{a}	252^{a}	271^{a}	247^{a}	468.0^{a}	419.3^{a}	70.2^{a}	64.5^{a}
T_2	237^{a}	207^{ab}	240^{b}	220^{b}	248^{ab}	223^{ab}	426.8^{ab}	377.9^{ab}	64.0^{ab}	58.2^{ab}
T_3	210^{b}	187^{bc}	212^{c}	196^{c}	231^{b}	207^{bc}	396.9^{ab}	352.0^{bc}	59.8^{ab}	54.2^{bc}
T_4	197^{c}	167^{c}	192^{d}	178^{d}	205^{c}	185^{c}	352.4^{b}	314.9^{c}	52.9^{b}	48.5^{c}
HSD ($p \le 0.05$)	*2.47*	*20.2*	*12.3*	*17.2*	*25.1*	*35.5*	*82.80*	*60.08*	*13.00*	*7.73*
Mulching practices (M)										
M_1	380^{a}	344^{a}	388^{a}	369^{a}	284^{a}	536^{a}	1003^{a}	910.7^{a}	151^{a}	140^{a}
M_2	109^{c}	90.8^{c}	127^{c}	107^{c}	24.8^{c}	21.4^{c}	42.60^{c}	36.37^{c}	6.39^{c}	5.60^{c}
M_3	173^{b}	149^{b}	174^{b}	159^{b}	109^{b}	90.0^{b}	187.0^{b}	151.1^{b}	28.1^{b}	23.2^{b}
HSD ($p \le 0.05$)	*7.93*	*11.7*	*14.0*	*12.5*	*20.8*	*20.2*	*58.83*	*33.53*	*7.70*	*4.56*
Tillage system (T) ×Mulching practices (M)										
$T_1 \times M_1$	380^{a}	358^{a}	451^{a}	423^{a}	659^{a}	607	1133^{a}	1031.3^{a}	169	159^{a}
$T_2 \times M_1$	380^{a}	350^{a}	396^{b}	367^{b}	604^{ab}	552	51.00^{cd}	42.50^{fg}	7.65	6.53^{ef}
$T_3 \times M_1$	380^{a}	346^{a}	368^{bc}	356^{bc}	568^{b}	517	219.6^{c}	184.1^{e}	32.9	28.3^{d}
$T_4 \times M_1$	380^{a}	322^{a}	339^{c}	328^{c}	505^{c}	468	1038^{ab}	937.8^{ab}	156	144^{ab}
$T_1 \times M_2$	122^{cd}	104^{c}	158^{e}	131^{e}	29.7^{ef}	25.0	45.30^{cd}	39.60^{g}	6.79	6.10^{ef}
$T_2 \times M_2$	120^{cd}	100^{cd}	128^{efg}	122^{ef}	26.3^{f}	23.3	196.7^{cd}	156.4^{ef}	29.5	24.1^{d}
$T_3 \times M_2$	112^{d}	95.7^{cd}	196^{d}	105^{ef}	22.7^{f}	20.3	973.3^{ab}	878.4^{bc}	146	135^{bc}
$T_4 \times M_2$	82^{e}	64.0^{d}	104^{g}	80.5^{f}	20.3^{f}	17.0	39.00^{d}	34.50^{g}	5.85	5.31^{ef}
$T_1 \times M_3$	212^{b}	194^{b}	214^{d}	203^{d}	128^{d}	108	178.3^{cd}	143.2^{efg}	27.0	22.0^{d}
$T_2 \times M_3$	210^{b}	170^{b}	196^{d}	182^{d}	114^{d}	92.1	868.6^{b}	795.2^{cd}	130	122^{c}
$T_3 \times M_3$	138^{c}	118^{c}	152^{ef}	128^{e}	104^{d}	84.3	35.00^{d}	28.90^{g}	5.25	4.44^{f}
$T_4 \times M_3$	130^{cd}	114^{c}	134^{efg}	126^{e}	89.3^{de}	71.0	153.7^{cd}	120.6^{efg}	23.1	18.6^{de}
HSD ($p \le 0.05$)	*19.3*	*39.3*	*37.4*	*38.1*	*60.4*	*68.6*	*180.5*	*114.84*	*NS*	*15.18*

Analysis of variance Source	*DF*										
T	3	*<0.01***	*<0.01***	*<0.01***	*<0.01**	*<0.01***	*0.005**	*0.015**	*0.005**	*0.02**	*0.002***
M	2	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***
T×M	6	*<0.01***	*0.001**	*<0.01***	*0.006**	*<0.01***	*0.001**	*0.04**	*<0.01***	*0.02**	*<0.01***

Note: T_1 = Zero tillage; T_2 = Cultivator 2 times + planking 1 time; T_3 = Cultivator 2 times + MB Plough 1 time + planking 1 time; T_4 = Cultivator 2 times + Chisel plough 1 time + planking 1 time; M_1 = No mulch; M_2 = Plastic mulch (300 cm wide; 8 µm thick); M_3 = Sorghum straw mulch applied at a rate of 5 tones ha^{-1}; DF = Degree of freedom; HSD = Honestly significant difference; Values (mean ± standard error, n = 3) sharing different lettering for a parameter are different significantly ($p \le 0.05$) by the Tukey's HSD test; NS = Not significant at $P > 0.05$; * = Significant at $P < 0.05$; ** = Significant at $P < 0.01$.

The 1000-grain weight was highest under T_4 (Chisel plough + cultivator + planking), with values of 273 g and 279 g in 2017 and 2018, respectively (Table 5). This represented a 10% and 11% increase compared to T_1 (Zero tillage), which had 1000-grain weights of 248 g and 253 g in 2017 and 2018, respectively. Straw mulch (M_3) resulted in a 1000-grain weight that was 6% and 7% more than in control (M_1), and 2% and 1% higher than polythene mulch (M_2) treatment. Tillage practices also significantly affected the grain yield, with T_4 (Chisel plough + cultivator + planking) resulting in the highest grain yield (7.02 t ha^{-1} and 7.36 t ha^{-1} in 2017 and 2018, respectively). This represented a 45% and 40% increase compared to T_1 (Zero tillage). Straw mulch (M_3) led to a 6%

and 4% higher grain yield compared to polythene mulch (M_2), and 9% and 8% higher grain yield compared to the control treatment (M_1).

Significant effect of tillage and mulching practices on biological yield was calculated, with T_4 (Chisel plough + cultivator + planking) producing the highest biological yield (19.2 t ha^{-1} and 19.9 t ha^{-1} in 2017 and 2018, respectively). This represented a 45% and 35% increase compared to T_1 (Zero tillage). Straw mulch (M_3) produced a 5% and 4% higher biological yield compared to polythene mulch (M_2), as well as 10% and 7% higher biological yield than the control treatment (M_1). The results indicate that T_4 (Chisel plough + cultivator + planking) and straw mulch (M_3) were the most effective treatments for improving maize growth and yield (Table 5).

Harvest index (%)

The tillage systems did not significantly affect harvest index, although Chisel plough + cultivator + planking (T_4) tended to result in a higher harvest index, with values of 37.60% and 37.81% in 2017 and 2018, respectively (Table 5). In contrast, zero tillage (T_1) tended to result in lower harvest indices, with values of 35.43% and 35.84% in 2017 and 2018, respectively. Mulching practices did not significantly influence the harvest index. However, in 2017, the no-mulching treatment (M_1) tended to result in a higher harvest index (36.87%), while in 2018, plastic mulching (M_2) tended to result in a lower harvest index (36.65%). The interactive effect of tillage and mulching on harvest index was not statistically significant (Table 5). These results suggest that while tillage and mulching practices may have some impact on harvest index, the differences were not statistically significant. Further research may be desired to fully recognize the effects of these treatments on harvest index.

Economic analysis

The economic analysis of the maize production experiment revealed significant variations in costs and returns across different treatments (Table 6). The entire cost of production extended from US$747 to US$1087 per hectare, depending on the combination of tillage systems and mulching strategies. The combination T_4M_3, which involved Cultivator 2 times + Chisel plough 1 time + planking 1 time (T_4) and Sorghum straw mulch (M_3), incurred the highest total cost of production. However, this treatment also generated the highest net income of US$719 per hectare. The economic viability of each treatment combination was evaluated by calculating its benefit-cost ratio (BCR). BCR varied from 0.39 to 1.82, with T_4M_3 demonstrating the maximum BCR of 1.82 (Table 6). Compared to the control treatment T_1M_1 (Zero tillage with No mulch), T_4M_3 resulted in a significant increase in net income, with a percentage increase of 146.5%. This suggests that the combination of T_4 and M_3 is a profitable option for maize production. In contrast, treatment T_2M_2 (Cultivator 2 times + planking 1 time with Plastic mulch) incurred the lowest net income, with a percent decrease of 61.2% compared to the control treatment (Table 6). Overall, the economic analysis highlights the importance of selecting the optimal combination of tillage and mulching practices to maximize economic returns in maize production. The results suggest that T_4M_3 is a promising option for farmers seeking to improve their economic returns.

DISCUSSION

Persistent weed seed bank

The study on the effect of tillage systems and mulching practices on weed seed density in the soil bank provides valuable insights into the dynamics of weed populations in agricultural ecosystems. The conducted inquiry revealed variations in germinable seed bank abundance throughout the course of two-year research period, with the conducted study determining a relatively small germinable seed bank size (up to 16,130 seeds m^{-2}) when compared to earlier studies (Zamljen et al., 2024; Romaneckas et al., 2021). The impact of weather conditions on weed seed banks is a crucial factor to consider in understanding the dynamics of weed populations. Although the conducted study did not experience extreme weather events such as drought or flooding, which can significantly influence weed seed formation (Singh et al., 2022), it is essential to acknowledge the potential role of weather conditions in shaping weed seed bank dynamics. Weather conditions can influence weed seed production, dormancy, and viability. For instance, drought can reduce weed seed production (Singh et al., 2022), while flooding can lead to seed decay (Dahlquist et al., 2007).

Table 5. Impact of various tillage systems and mulching practices on agronomic characteristics and yield parameters of maize during 2017 and 2018

Treatment		Plant height (cm)		1000-grain weight (g)		Grain Yield (t ha^{-1})		Biological Yield (t ha^{-1})		Harvest Index (%)	
		2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Tillage system (T)											
T_1		180.0^{c}	188.6^{d}	248.2^{c}	252.8^{c}	4.84^{c}	5.26^{c}	13.2^{c}	14.7^{d}	36.7	35.8
T_2		199.5^{bc}	211.3^{c}	257.8^{bc}	262.1^{bc}	5.52^{bc}	5.99^{b}	15.7^{b}	16.5^{c}	35.4	36.5
T_3		211.6^{b}	231.4^{b}	263.6^{ab}	270.1^{ab}	6.40^{ab}	6.74^{a}	17.1^{ab}	17.9^{b}	37.6	37.8
T_4		240.5^{a}	248.2^{a}	272.6^{a}	278.9^{a}	7.02^{a}	7.36^{a}	19.2^{a}	19.9^{a}	36.7	37.1
HSD ($p \leq 0.05$)		*24.11*	*15.62*	*9.75*	*11.97*	*0.93*	*0.69*	*2.23*	*1.30*	*NS*	*NS*
Mulching practices (M)											
M_1		201.1^{b}	212.8^{b}	256.1^{b}	263.1^{b}	5.68^{b}	6.12^{b}	15.5^{b}	16.6^{b}	36.9	36.9
M_2		206.9^{ab}	220.1^{ab}	260.9^{ab}	265.9^{ab}	5.92^{ab}	6.31^{ab}	16.3^{ab}	17.2^{ab}	36.3	36.7
M_3		215.8^{a}	226.7^{a}	264.6^{a}	268.9^{a}	6.23^{a}	6.58^{a}	17.1^{a}	17.8^{a}	36.6	36.9
HSD ($p \leq 0.05$)		*12.61*	*11.95*	*7.55*	*5.07*	*0.52*	*0.38*	*1.17*	*1.11*	*NS*	*NS*
Tillage system (T) ×Mulching practices (M)											
$T_1 \times M_1$		169.4	180.1	241.5	250.01	4.45	5.01	12.0	14.1	37.2	35.7
$T_2 \times M_1$		182.3	188.3	253.9	259.06	5.17	5.74	13.3	14.9	36.9	35.2
$T_3 \times M_1$		188.3	197.3	261.1	267.81	6.29	6.59	14.3	15.1	36.1	36.6
$T_4 \times M_1$		195.7	203.3	267.9	275.59	6.82	7.15	15.0	16.0	35.0	36.2
$T_1 \times M_2$		197.9	211.6	250.1	252.69	4.93	5.24	15.7	16.5	34.4	36.0
$T_2 \times M_2$		204.9	219.1	258.3	262.03	5.36	5.90	16.5	17.0	36.8	37.3
$T_3 \times M_2$		206.0	225.6	263.7	270.01	6.37	6.74	16.7	17.4	37.9	38.0
$T_4 \times M_2$		209.8	231.3	271.5	279.00	7.01	7.37	17.2	17.8	37.2	37.9
$T_1 \times M_3$		218.9	237.2	252.9	255.57	5.13	5.53	17.4	18.4	37.7	37.5
$T_2 \times M_3$		233.2	242.1	261.1	265.07	6.01	6.33	18.2	19.0	37.4	37.6
$T_3 \times M_3$		237.5	249.2	266.1	273.03	6.55	6.90	19.1	19.7	36.8	37.5
$T_4 \times M_3$		250.9	253.4	278.4	282.14	7.24	7.55	20.2	20.8	35.8	36.3
HSD ($p \leq 0.05$)		*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Analysis of variance Source	*DF*										
T	*3*	*0.001**	*<0.01***	*0.020**	*0.001**	*0.001***	*0.001**	*<0.01***	*0.001**	*0.897^{NS}*	*0.898^{NS}*
M	*2*	*0.026**	*0.034**	*0.034**	*0.034**	*0.049**	*0.049**	*0.001***	*0.009***	*0.919^{NS}*	*0.918^{NS}*
T×M	*11*	*0.976^{NS}*	*0.974^{NS}*	*0.974^{NS}*	*0.973^{NS}*	*0.927^{NS}*	*0.927^{NS}*	*0.927^{NS}*	*0.927^{NS}*	*0.958^{NS}*	*0.958^{NS}*

Note: T_1 = Zero tillage; T_2 = Cultivator 2 times + planking 1 time; T_3 = Cultivator 2 times + MB Plough 1 time + planking 1 time; T_4 = Cultivator 2 times + Chisel plough 1 time + planking 1 time; M_1 = No mulch; M_2 = Plastic mulch (300 cm wide; 8 μm thick); M_3 = Sorghum straw mulch applied at a rate of 5 tones ha^{-1}; DF = Degree of freedom; HSD = Honestly significant difference; Values (mean ± standard error, n = 3) sharing different lettering for a parameter are different significantly ($p \leq 0.05$) by the Tukey's HSD test; NS = Not significant at $P > 0.05$; *= Significant at $P < 0.05$; ** = Significant at $P < 0.01$.

Additionally, weather conditions can also impact seed dormancy, with certain conditions inducing or breaking dormancy (Battla and Benech-Arnold, 2007). The results suggest that cropping system, mulching, and the intensity of the tillage were key elements in deciding the sizes of weed seed bank at different depths. Vertical distribution of weed seed in soil is directly influenced by various tillage practices which alter the weeds abundance in crop field (Ameena et al., 2024). Tillage practices govern vertical and horizontal seeds dispersal in different soil profiles (Ameena et al., 2015).

The performed research revealed that intensive soil cultivation resulted in a notable decline in weed seed germination, surpassing the effects of conservation tillage and zero till practices. This decrease can be attributed to heightened seed susceptibility to predators, stemming from soil disruption and surface-level seed accumulation (Trichard et al., 2013). Notably, annual seed predation rates can be substantial, influencing both current and future weed populations (Davis et al., 2013; Westerman et al., 2003). The relationship between tillage and weed seed distribution is complex, with soil characteristics like structure and compaction affecting the outcome of tillage operations (Colbach et al., 2000). Tillage can also impact seed dormancy, influencing weed seedling emergence patterns (Ghersa et al., 1992). Prior agricultural practices, including shallow tillage for cover crops, may have long-term effects on weed seed distribution, potentially leading to patchy weed growth.

The obtained results support the notion that tillage-induced changes in soil conditions, such as increased light and nitrogen availability, can trigger weed seed germination (Hossain and Begum, 2015; Travlos et al., 2020). However, contradictory findings also have been reported, highlighting the complexity of the relationship between tillage and weed seed bank dynamics (Ruisi et al., 2015; Zamljen et al., 2024). Research proposes that soil disturbance has a key function in determining the vertical distribution of weed seeds, with more intense disturbance often leading to a greater number of weed seeds near the upper soil surface (Feledyn-Szewczyk et al., 2020). However, few findings also have reported that tillage intensity may not necessarily alter the vertical movement of weed seeds, highlighting the complexity of this relationship (Santín-Montanyá et al., 2013).

In the case of mulching, the study highlights the impact of mulching practices on weed seeds bank density. The obtained results show that mulched plots had lower weed seed bank density compared to no-mulched plots, suggesting that mulch prevented weed seed germination (Ameena et al., 2024). The physical barrier created by mulch, whether organic or synthetic, can suppress weed growth and reduce seed production (Elmer, 2000). The type of mulch used can also influence weed seed bank density. Organic mulches, such as sorghum straw, can have allelopathic effects on weeds, reducing their growth and seed production (Westerman et al., 2005). Similarly, plastic mulches can cause soil solarization, increasing soil temperature and killing weed seeds (Lee and Christian, 2017). The increased temperature under plastic mulch can be detrimental to weed seeds, especially those sensitive to temperature fluctuations (Nijjer et al., 2002). The decline in weed seed bank under mulched plots can be ascribed to numerous factors, including increased seed predation and reduced germination. Mulched plots can provide a favorable environment for beneficial insects, such as granivorous (carabid beetles), which are imperative seed eaters (Armstrong and McKinlay, 1997; Westerman et al., 2003). Additionally, mulch can reduce the variables that promote germination of weed seeds, including light and temperature fluctuations (Kelton et al., 2011).

Relative abundance and weed growth

The study highlighted the impact of tillage techniques and mulching practices on weed characteristics, including density and fresh and dry weight. The obtained results show that different weed species responded differently to various tillage and mulching techniques, with nine out of fifteen weed types found in both soil weed seeds banks and weed flora (Shah and Khan, 2006; Mohammad et al., 2007). Observations indicate that broadleaf weeds outcompeted grassy weeds in the initial stages of growth of maize, potentially due to their adaptability and competitive advantage (Shah and Khan, 2006). This trend is consistent with existing research highlighting the challenges posed by broadleaf weeds in various crops, underscoring the need for targeted management strategies.

The impact of tillage systems on weed presence and dry weight was significant, with higher values observed in chisel plough and MB plough tillage systems compared to zero tillage systems. This is coherent with prior findings stating that reduced tillage practices can lead to an abundance of weed seeds that survive, sprout, and develop close to the soil surface (Buhler, 1995). In contrast, deep tillage systems can bury weed seeds, reducing their germination and emergence (Mohler et al., 1993). The effectiveness of deep tillage in reducing weed density can be attributed to the burial of weed seeds, which can prevent their germination and emergence. This approach can be a useful cultural practice for weed management, especially when combined with shallower tillage techniques in subsequent years (Mohler et al., 1993). However, the impact of tillage techniques on weed density can vary relying on locality and year, with some studies showing that minimum and zero-tillage treatments can have higher weed densities (Blackshaw et al., 1994). The shift from conventional to zero or reduced tillage systems can also central to increased herbicide use, as these systems are more prone to weed growth (Steckel et al., 2007). However, long term weed management through conservation tillage can be an operative approach, as it can lead to a decline in weed density due to decomposition, germination in adverse environmental circumstances, and weed seed predation.

Yield and yield attributes

The study highlights the influence of tillage and mulching on maize performance, and yield. Deep tillage significantly improved maize productivity by enhancing soil physical attributes, like porosity and water infiltration (Wasaya et al., 2011). This led to better root growth, nutrient uptake, and increased yields (He et al., 2018; Wang et al., 2022). The interactive effect of deep tillage and sorghum straw mulch lead to the highest maize yield, likely due to improved soil physical properties, increased nutrient uptake, and enhanced water use efficiency (Silva and Cook, 2003; Jordan et al., 2010). Straw mulch, in particular, improved soil moisture retention, reduced soil temperature fluctuations, and promoted soil biota activity, important to increased plant height, 1000-grain weight and final yields (Ehsanullah et al., 2015; Rafiq et al., 2010). The impact of plastic mulch on maize growth is multifaceted, with effects on root zone temperature, microbial life, and soil properties (Amare and Desta, 2021). While plastic mulch can enhance growth and yield (Li et al., 2018; Torres-Olivar et al., 2018; Shah Jahan et al., 2018; Sarkar et al., 2019), its use also poses environmental risks, such as soil pollution from plastic fragments. Careful consideration of factors like cropping season, root zone temperature, and crop type is necessary to mitigate these risks. This nuanced approach can help balance the benefits and drawbacks of plastic mulch use.

Economic analysis

The economic analysis revealed that deep ploughing with straw or plastic mulch was the highest profitable, resulting in the maximum net income and benefit cost ratio (BCR). This is accredited to improved soil physical attributes and increased crop yield associated with deep ploughing (Borghei et al., 2008; Tao et al., 2015). The use of sorghum straw mulch further enhanced economic benefits by soil moisture conservation, weeds suppression, and soil temperature regulation (Sharma et al., 2010). Deep ploughing with straw mulch can lead to enhanced maize productivity, soil health, and increased economic benefits, contributing to food security, poverty reduction, and sustainable agricultural development. This approach also improves water use efficiency (WUE) and reduces water consumption (Yin et al., 2015; Bai et al., 2019; Sun et al., 2020). Straw mulch improves physical attributes of soil, regulates soil hydrothermal properties, and increases the content of soil organic matter, ensuring an adequate water availability during critical stages of crop growth (Yingchen et al., 2014; Liu et al., 2019).

CONCLUSIONS

The study demonstrates the significant impact of tillage systems and mulching practices on weed dynamics, maize growth, yield, and economic returns. The key findings are: use of moldboard plough (T_3) and polythene mulch (M_2) significantly reduced weed seed density at various soil depths, with a reduction of 39.6% and 48.7% at 0–5 cm depth, respectively. Similarly, Chisel plough + cultivator + planking (T_4) and polythene mulch (M_2) significantly reduced weed density, with a reduction of 28.5% and 73.1% at harvest, respectively. The use of Chisel plough + cultivator + planking (T_4) and polythene mulch (M_2) significantly reduced weeds fresh and dry biomass, with a reduction of 67.1% and 92.1% in fresh biomass, and 62.2% and 91.4% in dry biomass, respectively. Likewise, Chisel plough + cultivator + planking (T4) and straw mulch (M3) significantly increased grain yield, with an increase of 45% and 6% compared to zero tillage and no mulching, respectively. The combination of T_4 and M_3 incurred the highest total cost of production but generated the highest net income (US$719 per hectare) and benefit-cost ratio (1.82), with a percent increase of 146.5% compared to the control treatment. Overall, the study suggests that the adoption of deep tillage (Chisel plough + cultivator + planking) and straw mulch could be a profitable option for maize production by reducing weed density and biomass and increasing crop yield and economic returns. By bridging the knowledge gap in the integrated effects of tillage systems and mulching practices on weed dynamics and maize productivity, this study provides valuable insights for farmers and policymakers seeking to optimize maize production while minimizing environmental impacts. The findings of this study can help making informed decisions regarding the development of sustainable agricultural practices that enhance crop yields, reduce weed pressure, and promote economic viability. Ultimately, this research contributes to the advancement of sustainable agriculture and food security in regions where maize is a staple crop.

Acknowledgments

The authors sincerely acknowledge the University of Agriculture, Faisalabad, Pakistan for providing funding and support for this research and all the collaborators who assisted to execute this study.

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