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Synergistic Effects of Crop Establishment Methods and Weed Management on Maize (*Zea mays* L.) Productivity and Water Utilization

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Abstract

The Indo-Gangetic plains are experiencing significant climate variability and groundwater depletion, threatening agricultural productivity and water security. The dominant Rice-Wheat (RW) cropping pattern exacerbates water scarcity, necessitating the replacement of water-intensive crops like rice with more water-efficient alternatives. Maize, a primary *kharif* crop, but due to its spacious nature and slow initial growth, it is prone to heavy weed growth, leading to water and nutrient losses. To optimize resource utilization and maintain sustainable maize yields, alternative agronomic strategies are required. Modifying planting systems and implementing effective weed management practices show promise in improving crop and water productivity of maize. So, keeping all this in view, an experiment was conducted for two years including crop establishment methods *viz.*, bed + residue, zero tillage (ZT) with residue and conventional tillage (CT) + residue in main plots and five weed management options as pyroxasulfone (PE), pyroxasulfone (PE) *fb* tembotrione (PoE), atrazine (PE) *fb* tembotrione (PoE), weedy check and weed free check (sub plots) were compared in a split-plot design with three replications. Results indicated that bed + residue (Bed+R) recorded highest soil moisture content (11.84 % at knee height and 11.86 % at flowering stage in 0-15 cm of soil depth) and water productivity (9.72 kg-ha mm^{-1}) compared to ZT+R and CT+R. Among weed management options, highest soil moisture content and water productivity was recorded with weed free plot, but in sequential herbicide options, highest soil moisture content (12.35 % at knee height and 12.37 % at flowering stage in 0-15 cm of soil depth) and water productivity (10.30 kg-ha mm^{-1}) was recorded with pyroxasulfone *fb* tembotrione compared to other treatments. Overall, based on the findings it can be concluded that pyroxasulfone *fb* tembotrione application in maize with bed planting enhances water productivity with lesser infestation of weeds under Indo-Gangetic Plains of India.

Abbreviations

IGP: Indo-Gangetic Plains
RW: Rice-wheat
WFC: weed free check
WC: weedy check
ZT: zero tillage
CT: conventional tillage
PE: pre-emergence
PoE: post-emergence
DAS: days after sowing
Fb: followed by

Introduction

Zea mays L. (maize) is the third most prominent cereal crop in India, after *Oryza sativa* (rice) and *Triticum aestivum* (wheat), exhibiting exceptional adaptability to diverse agro-climatic conditions and possessing the highest genetic yield potential among cereals (Shankala *et al.*, 2022). India ranks fourth globally in terms of maize cultivation area and seventh in production, accounting for approximately 4% of global maize area and 2% of total production. Maize is one of the sensitive crops to water stress (either drought or excess water). Notably, over 70 % of *kharif* maize is cultivated under rainfed conditions, which exposes the crop to numerous biotic (weeds, pests and diseases) and abiotic stresses, including drought, heat, and flooding (Shankala *et al.*, 2022). The stress-prone ecology of kharif maize (*Zea mays* L.) contributes to its relatively low productivity (2965 kg ha^{-1}), which is primarily cultivated under assured ecosystem conditions. Crop establishment methods comprise a suite of techniques employed by farmers to initiate and cultivate crops in a field, significantly influencing crop development, yield, and the overall sustainability of agricultural systems. Certain methods specifically facilitate the conservation of resources such as land, soil, water, and energy while effectively managing weed growth in the field, thereby promoting eco-friendly and sustainable agricultural practices (Das *et al*., 2016). In bed planting systems along with residue retention, crops are cultivated on elevated beds, alternating with furrows, to optimize water use efficiency by reducing the evaporation losses (Kumar S. *et al*., 2021). The beds are typically designed to accommodate crops of suitable sizes, with irrigation water applied in the intervening furrows. This configuration enables crop diversification through intensified water use, fostering more efficient water utilization under both rainfed and irrigated conditions (Jat *et al*., 2008, Kaur *et al*., 2023, 2024). The bed planting system facilitates optimum water storage and safe disposal of excess water, making it an attractive strategy for enhancing crop productivity while minimizing water loss. Given the pressing need to increase crop production, the development of high-yielding, water-saving agricultural practices has become a paramount priority for achieving sustainable agricultural development in India, necessitating the implementation of efficient agricultural water use strategies that prioritize water conservation and reduced environmental impact.

Weeds constitute a paramount biotic constraint on global agricultural productivity, posing a significant threat to crop yields. According to estimates by the Weed Loss Committee of the Weed Science Society of America, unmanaged weed populations can precipitate substantial yield reductions of up to 50% in *Zea mays* L. (maize) (Soltani *et al*., 2016). This emphasizes the imperative for efficacious weed management strategies to mitigate crop losses and ensure food security. In India, weed infestations have been reported to cause significant yield losses in maize (*Zea mays* L.), with estimates suggesting a 49 % reduction in productivity (Gharde *et al*., 2018). Weeds engage in competition with crops for primary resources such as water, light, nutrients, and spatial occupancy, thereby limiting agricultural production. The implications of crop-weed competition have predominantly been quantified in terms of reduced crop productivity and yield, rather than focusing on the weed species themselves (Zimdahl, 2007). Owing to their superior ability for soil water exploration (Stuart *et al*., 1984), greater effective root zone and soil volume per plant, rapid development of extensive root systems, greater resource affinity, and higher tolerance to climatic variation than most of the crops (Zimdahl, 2018), weeds often demand more water than many crops. This highlights that, to increase the water use efficiency or water productivity of crop there is need for effective weed management strategies and mitigate yield losses. In view of above, the present research was planned to evaluate the combined effect of treatments on maize crop yield and water productivity.

Materials and methods

Experimental site and treatments

The experiments were conducted at ICAR-Indian Agricultural Research Institute, New Delhi (28°64' N latitude, 77°15' E longitude and altitude of 228 meters above mean sea level) during rainy (*kharif*) seasons of 2021 and 2022. In main plots, treatments consisting of crop establishment methods with residue whereas in sub-plots five treatments involving weed management options/ herbicides (Table 1) were laid out in a split plot design with three replications. Maize was followed by wheat crop and maize-wheat cropping system was followed for the last five years on the same piece of experimen-

Table 1 - Treatment details adopted in the experiments during 2021 and 2022

Treatments	Treatment abbreviations	Treatment code
Main Plot (Crop Establishment methods)		
Bed planting + retention of crop residue* @ 3t ha^{-1}	Bed + residue	Bed
Zero tillage + retention of crop residue@ 3t ha^{-1}	ZT + residue	ZT
Conventional tillage + incorporation of crop residue @3t ha^{-1}	CT + residue	CT
Sub-plot (Weed management options)		
Pyroxasulfone 85WG @ 0.15 kg ha^{-1} (PE)	Pyroxa.	W_1
Pyroxasulfone @0.15 kg ha^{-1} (PE) fb tembotrione @ 0.10 kg ha^{-1} (PoE)	Pyroxa. fb tembo.	W_2
Atrazine (PE) @1.0 kg ha^{-1}fb tembotrione @ 0.10 g ha^{-1} (PoE)	Atra. fb tembo.	W_3
Weedy check	WC	W_4
Weed free check	WFC	W_5

Residue* (wheat residue was used), PE- pre-emergence; PoE-post emergence

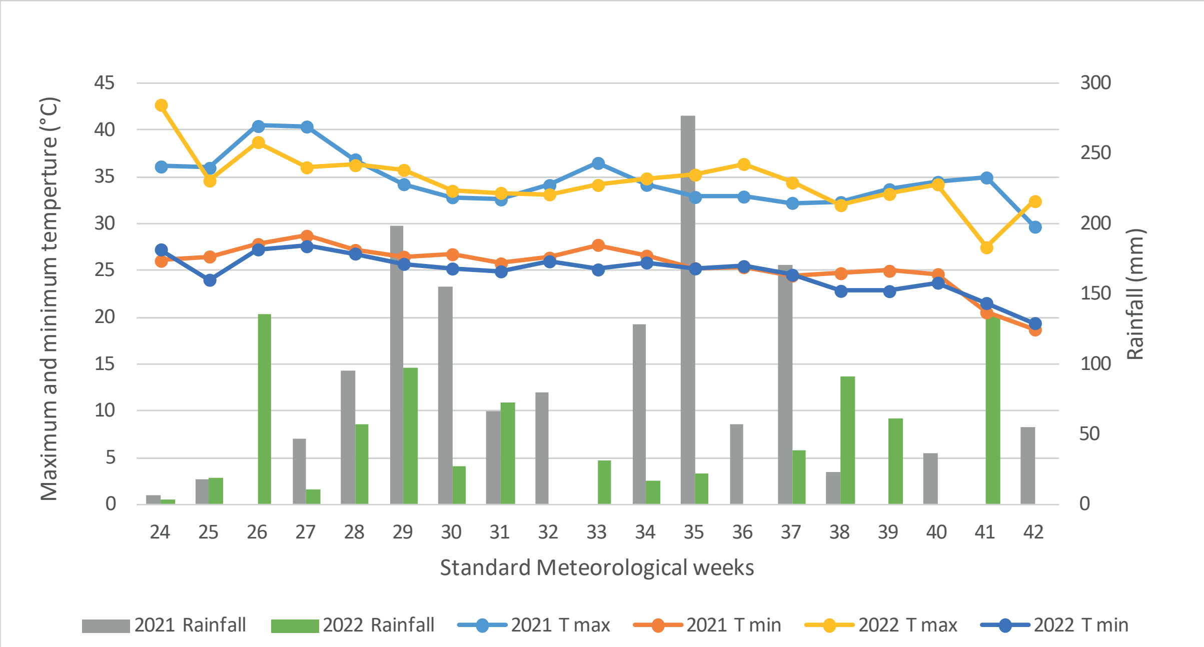

Fig. 1 - Standard meteorological weeks during 2021 and 2022 experimentations

tal unit. Among the weed treatments, weedy check (WC) shows a natural uninterrupted weed infestation. The soil was sandy loam with a moderate water holding capacity. The field had an even topography and a well-functioning drainage system. The upper 15 cm soil was found to be low in organic C (0.41), low in available N (221.3 kg ha^{-1}), medium in available P and K (18 and 241.1 kg ha^{-1}), and slightly alkaline in soil reaction (7.8).

The climatic conditions exhibited interannual variability between the two experimental periods (Fig. 1). Specifically, the precipitation patterns in the first year (2021) of the study displayed significant variation in comparison to the second year (2022), characterized by a more uniform distribution of rainfall.

Crop sowing and agronomic practices

The maize seeds were sown in lines at row-to row distance of 60 cm and plant to plant 15 cm during both the years. In case of bed planting, bed planter was used. Maize variety Pusa Jawahar Hybrid Maize-1 (PJHM-1) seeds were sown at the rate of 18 kg ha^{-1} to maintain the optimum plant stand. Pusa Jawahar Hybrid Maize-1 (PJHM-1) is a medium maturing (90-95 days), medium tall (195 cm) hybrid, having dark foliage, semi-erect leaves with stay green character. Seeds of this hybrid are semi-dent, bold and orange/amber in colour. Maize seeds were treated with fungicide (carbendazim) before sowing to prevent fungal damage. Application of 180 kg nitrogen ha^{-1}, 60 kg ha^{-1} of phosphorous and 60 kg ha^{-1} of potassium was done in maize. Full doses of P and K and 33% N were applied as basal. The remaining N was top dressed in two equal splits at 25 DAS (33%) and 55 DAS (34%).

Yield (t ha^{-1})

Grain and Biomass yield (grain+stover) were estimated at 12.5% and 18% moisture content based on the net plot area corresponding to each treatment.

Moisture content (Gravimetric method)

The soil samples were collected from each experimental unit from 15 and 30 cm depth with the help of soil auger. The fresh soil from samples were taken in a moisture box and labelled it properly. The fresh weight of soil samples with moisture boxes was taken. The soil moisture boxes with soil samples were placed in the oven set at 105°C ± 5°C, for a couple of days for getting the constant weight or till they attain a constant weight and weighed. The weight of water removed and moisture content (%) were calculated as follows.

Weight of water = Weight of wet sample - Weight of dry sample

$$\text{Moisture content (\%)} = \frac{\text{(Weight of water)}}{\text{(Weight of dry soil)}} \times 100$$

Water productivity

Water productivity was computed as a ratio between Grain yield and total water used. It was calculated by the following:

$$\text{Water productivity (kg ha-mm}^{-1}\text{)} = \frac{\text{(Grain yield (kg)}}{\text{(Water requirement (ha-mm)}}$$

Statistical analysis

Data on soil moisture, water productivity and maize crop were analysed by the analysis of variance (ANOVA) technique for a split-plot design using PROC GLM in SAS 9.3 (SAS Institute, Cary, NC). The error variances for almost all parameters (i.e., soil moisture, water productivity and maize grain yield) were homogeneous over the years, indicating that the uniformity in error variance was significant. Hence, pooled analysis was done to find out the effects of the year (Y), crop establishment methods (C) and weed management options (W) on the studied variables of soil moisture and maize, and data are presented year-wise. The significance of treatment means was appraised using Tukey's honest significant difference (HSD) test at p ≤.05.

Results and Discussion

Moisture content at knee height and flowering stage

The soil moisture content at different soil depths and at different maize developmental stages were influenced by years, crop establishment methods and weed management options (Table 2). A pooled analysis of two-year data revealed that non-significant effects on soil moisture content at different depths and different stages were observed due to years effect. Among different crop establishment methods, significantly higher soil moisture content (11.84 % and 11.86 %) at 0 -15 cm of soil depth was observed under bed + residue (Bed+R) compared to ZT+R and CT+R at knee height stage and flowering stage respectively. But lower layers (15-30 cm) did not show significant differences in soil moisture recorded at flowering stage between bed + residue (Bed+R) and ZT+R but CT+R recorded significantly lower soil moisture.

A comparative analysis of various weed management options revealed that the weed-free check exhibited significantly higher soil moisture content (12.65% and 12.78% at 0-15 cm soil depth, and 8.87% and 8.89% at 15-30 cm soil depth) compared to all other treatments during the knee height and flowering stages, respectively. However, in the case of sequential herbicide treatment, pyroxa *fb* tembotrione (W_2) demonstrated significantly higher soil moisture content (12.35% and 12.37% at 0-15 cm soil depth, and 8.64% and 8.85% at 15-30 cm soil depth) compared to other herbicide treatments during the knee height and flowering stages, respectively. Contrary to that, the weedy check (W_4) exhibited the lowest soil moisture content values across different soil depths and growth stages.

Yield t ha^{-1} (Grain and Biomass)

The grain yield and biomass yield of maize were influenced by years, crop establishment methods and weed management options (Table 3). A two-year pooled analysis revealed that annual variability had no significant impact on maize grain and biomass yields (Table 3). However, bed planting with residue (Bed + R) resulted in significantly higher grain yield (7.03 t ha^{-1}) and crop biomass (13.71 t ha^{-1}) compared to zero-tillage with residue (ZT+R) and conventional tillage with residue (CT+R). Among various weed management options, the highest grain yield (8.20 t ha^{-1}) and biomass yield (15.03 t ha^{-1}) were achieved in treatment W_5, while the lowest yields (4.12 t ha^{-1} and 9.67 t ha^{-1}, respectively) were recorded in the weedy check (W_4). Sequential herbicide applications resulted in higher yields, with treatments pyroxa *fb* tembotrione (W_2) achieving the highest grain yield (7.46 t ha^{-1}) and biological yield (14.58 t ha^{-1}), respectively. Notably, pyroxa *fb* tembotrione demonstrated a 44.77 % yield increase over the weedy check (WC) across the two-year study period.

Table 2 - Soil Moisture content (%) at different depths and different growth stages as influenced by crop establishment methods and weed management options (pooled data of two years)

Treatments	Soil Moisture (%)			
	Knee height stage		Flowering stage	
Year	0-15 cm	15-30 cm	0-15 cm	15-30 cm
2021	11.51^a	8.12^a	11.64^a	8.14^a
2022	11.56^a	8.10^a	11.61^a	8.12^a
Crop establishment methods				
Bed + residue	11.84^a	8.36^a	11.86^a	8.22^a
ZT+ residue	11.73^b	8.28^b	11.80^b	8.21^a
CT+ residue	11.25^c	7.86^c	11.24^c	7.82^b
Weed management options				
Pyroxasulfone	11.34^c	7.92^d	11.35^c	7.93^c
Pyroxasulfone fb Tembotrione	12.35^b	8.64^b	12.37^b	8.65^b
Atrazine fb Tembotrione	12.22^b	8.55^c	12.28^b	8.56^b
Weedy check	9.34^d	6.53^e	9.34^d	6.54^d
Weed free check	12.65^a	8.87^a	12.78^a	8.98^a

Water Productivity (kg ha-mm^{-1})

An analysis of water productivity in maize revealed significant influences from annual variability, crop establishment methods, and weed management options (Table 3). A two-year pooled analysis showed that water productivity was significantly higher in the second year (9.41 kg ha-mm^{-1}) of experimentation compared to the first year (7.47 kg ha-mm^{-1}). Among crop establishment methods, bed planting with residue (Bed+R) resulted in significantly higher water productivity (9.72 kg ha-mm^{-1}) than zero-tillage with residue (ZT+R) and conventional tillage with residue (CT+R). In terms of weed management options, the weed-free check (W_5) exhibited significantly higher water productivity (11.32 kg ha-mm^{-1}) compared to other treatments. Sequential herbicide applications also demonstrated higher water productivity, with pyroxa fb tembotrione (W_2) achieving the highest water productivity (10.30 kg ha-mm^{-1}) among herbicide treatments. Conversely, the weedy check (W_4) exhibited the lowest water productivity (5.69 kg ha-mm^{-1}).

Discussion

Among various crop establishment methods, bed planting with residue (Bed+R) exhibited significantly enhanced soil moisture retention at 0-15 cm soil depth during knee height and flowering stages. This phenomenon can be attributed to the mulching effect of retained crop residue, which substantially reduces weed density and dry matter, thereby minimizing soil water evapotranspiration (Sharma *et al.*, 2023, Tisdale, 1993; Jabran and Chouhan, 2015). The elevated soil moisture content observed in the bed + residue can be attributed to the increased soil volume available for water retention, resulting in reduced losses due to evaporation and surface percolation. This finding is consistent with the results reported by Vijay *et al.* (2022), Solanki *et al.* (2019) and Savani *et al.* (2017). The increased soil volume in broad beds provides a greater capacity for water storage, thereby reducing the likelihood of water loss through evaporation and surface runoff. This is particularly important in water-scarce regions, where optimizing soil moisture content is crucial for crop growth and productivity (Kaur *et al.* (2020), Huang, C. *et al.* (2022) and Vijay *et al.* (2022). These findings suggest that bed planting with residue is an effective strategy for conserving soil moisture, particularly in the topsoil layer, during critical maize growth stages.

Yield and water productivity

Overall, the higher grain and biomass yield in bed + residue can be attributed to reduced water losses and improved growing conditions. The favourable microclimatic conditions available for the bed-sown crop, combined with optimum moisture supply, resulted in higher grain yield. The loose soil in beds provided sufficient space for better growth, leading to improved plant vigour, wider leaf area, increased crop biomass, and better translocation of photosynthates to grains, ultimately resulting in higher grain yield (Table 3). This finding is consistent with previous studies by Jehan *et al.* (2012), Zhaoquan *et al.* (2018), Kaur *et al.* (2020), and Huang *et al.* (2022). Additionally, the higher yield in the weed-free check is due to the absence of weed competition, which increased water availability for maize growth, leading to higher yields. Similarly, sequential herbicide application resulted in higher yields due to effective weed control, reducing competition for resources and minimizing water loss from the field.

Statistically significant differences in water productivity of maize were observed between the two years of the experiment. Notably, the second year exhibited higher water productivity compared to the first year. This discrepancy can be attributed to the variability in rainfall

Table 3 - Yield and water productivity of maize as influenced by crop establishment methods and weed management options (pooled data of two years)

Treatments	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})	Water Productivity (kg ha-mm^{-1})
Year			
2021	6.77^{a}	13.53^{a}	7.47^{b}
2022	6.88^{a}	13.65^{a}	9.41^{a}
Crop establishment methods			
Bed + residue	7.03^{a}	13.71^{a}	9.72^{a}
ZT+ residue	6.71^{a}	13.53^{a}	9.27^{b}
CT+ residue	6.71^{a}	13.53^{a}	9.23^{b}
Weed management options			
Pyroxasulfone	6.98^{c}	14.21^{b}	9.64^{c}
Pyroxasulfone fb Tembotrione	7.46^{b}	14.58^{b}	10.30^{b}
Atrazine fb Tembotrione	7.34^{b}	14.48^{b}	10.12^{b}
Weedy check	4.12^{d}	9.67^{c}	5.69^{d}
Weed free check	8.20^{a}	15.03^{a}	11.32^{a}

patterns between the two years. Specifically, the first year received higher and more uneven rainfall (Fig-1), resulting in increased losses due to seepage and surface runoff. In contrast, the second year experienced more evenly distributed rainfall, leading to reduced water losses and consequently higher water productivity. Among various crop establishment methods, Bed + residue exhibited significantly higher water productivity compared to ZT+ residue and CT+ residue. The elevated water productivity in Bed+residue can be attributed to increased grain yield and reduced water losses due to seepage and surface runoff. Additionally, the bed configuration creates a more favourable environment for growth, leading to efficient utilization of water. The reduced water losses and improved growing conditions in Bed+residue result in higher water productivity (Kumar *et al.*, 2022), making it a more water-efficient crop establishment method. Similar results have been published by Huang, *et al.* (2022), Kaur *et al.* (2020) and Vijay *et al.* (2022). The higher water productivity observed in the weed-free check can be attributed to the absence of water loss due to weed competition, resulting in increased water availability for maize growth. Weeds pose significant competition for resources such as water and nutrients, leading to their depletion from the soil and reduced maize growth (Zimdahl 2018 and Stuart *et al.* 1984). In contrast, the weedy check plot experienced intense competition for water and nutrients, resulting in reduced maize growth and yields. However, the sequential application of herbicides effectively controlled weeds, reducing competition for resources and minimizing water loss. This led to increased biological growth and ultimately, higher maize yields.

Conclusions

Bed planting with residue and effective weed management strategies significantly improved maize yield and water productivity. Bed planting reduced water losses and created favourable growing conditions, while weed management strategies minimized competition for resources. These findings are consistent with previous studies, highlighting the importance of effective weed control and optimal soil conditions for improving crop yields. Overall, these strategies can contribute to sustainable maize production and water resource management.

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