

Optimizing Maize (*Zea mays* L.) Productivity and Economic Returns through Sequential Herbicide Applications in the Semi-Arid Bundelkhand Region of India

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Abstract

Weed infestation is one of the most critical constraints limiting maize productivity, particularly under semi-arid conditions where crop-weed competition is intense during early growth stages. The present study aimed to evaluate the effectiveness of integrated weed management (IWM) practices on weed dynamics, crop performance, and economic returns of maize in the Bundelkhand region of Uttar Pradesh, India. A field experiment was conducted during the Kharif season of 2025 at the Agricultural Research Farm, Nehru Mahavidyalaya, Lalitpur, using a randomized block design (RBD) with nine treatments and three replications. The treatments included weedy check, weed-free condition, sole herbicidal and manual methods, and integrated approaches combining pre- and post-emergence herbicides. Observations on weed density, weed dry matter, weed control efficiency (WCE), growth parameters, yield attributes, grain yield, and economic returns were recorded. Results revealed that integrated approaches significantly outperformed individual methods. The sequential application of atrazine (pre-emergence) followed by tembotrione (post-emergence) proved most effective, achieving over 90% weed control efficiency with minimum weed density and dry matter. This treatment recorded a grain yield of 54.2 q ha⁻¹, which was statistically comparable to the weed-free treatment (58.4 q ha⁻¹), along with superior growth and yield attributes. Economic analysis indicated that this treatment resulted in the highest net returns with a benefit-cost ratio of 3.04. Thus, integrated weed management, particularly the combination of atrazine and tembotrione, offers an efficient, economically viable, and sustainable strategy for improving maize productivity under semi-arid conditions.

Keywords: Integrated weed management; maize (*Zea mays* L.); atrazine; tembotrione; weed control efficiency; grain yield.

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, contributing significantly to food security, livestock feed, and industrial raw materials. It is widely recognized as the “Queen of Cereals” due to its high genetic yield potential and adaptability across diverse agro-climatic conditions. Globally, maize accounts for nearly 13% of total crop production, making it one of the dominant crops alongside rice and wheat. In India, maize is placed in the third position among cereals after rice and wheat, playing a vital role in the agricultural economy and supporting sectors such as poultry, starch, and biofuel industries [1]. The demand for maize is continuously increasing due to its multifaceted uses and expanding industrial applications, with projections indicating substantial growth in production requirements by 2025 [2]. Despite its high yield potential, maize productivity is often constrained by several biotic and abiotic factors, among which weed infestation is considered one of the most serious yield-limiting constraints. Weeds compete aggressively with crops for essential resources such as nutrients, water, light, and space, thereby significantly reducing crop growth and yield. Globally, yield losses due to weeds in maize are estimated

to be around 37%, highlighting the magnitude of the problem [3]. In India, the extent of yield loss due to weeds varies widely from 28% to as high as 93%, depending on the intensity of infestation and management practices [4-5]. Recent studies also indicate that uncontrolled weed growth can reduce maize yield by up to 86%, emphasizing the economic importance of effective weed management. The critical period of crop-weed competition in maize generally occurs between 20 and 45 days after sowing (DAS), during which weed interference can cause irreversible yield losses if not managed effectively. Traditionally, farmers rely on manual weeding and mechanical methods to control weeds. Although effective, these methods have several limitations. Manual weeding is highly labor-intensive, time-consuming, and increasingly costly due to labor shortages during peak agricultural seasons. Moreover, it is often constrained by unfavorable weather conditions, particularly during the rainy season when field operations become difficult. On the other hand, chemical weed control through herbicides offers a rapid and cost-effective alternative. Herbicides such as atrazine are widely used as pre-emergence treatments due to their broad-spectrum efficacy.

However, continuous reliance on a single herbicide can lead to shifts in weed flora, development of herbicide resistance, and environmental concerns [6-7]. Recent research emphasizes that herbicide-only approaches are insufficient for sustainable weed management and may result in long-term ecological risks.

To overcome these limitations, the concept of Integrated Weed Management (IWM) has gained prominence in modern agriculture. IWM involves the judicious combination of cultural, mechanical, and chemical methods to manage weed populations below the economic threshold level while minimizing environmental impacts. This approach ensures effective weed control throughout the crop growth period and enhances resource-use efficiency. Studies have demonstrated that integrated approaches, particularly the combination of pre- and post-emergence herbicides, provide superior weed control efficiency and higher crop yields compared to individual methods. Furthermore, IWM strategies help delay the development of herbicide resistance and promote sustainable crop production systems [8-9]. The Bundelkhand region of Uttar Pradesh represents a unique agro-ecological zone characterized by semi-arid climate, erratic rainfall, degraded soils, and limited agricultural inputs. Agriculture in this region is predominantly rainfed, making crop production highly vulnerable to environmental stresses. Maize is an important crop in Bundelkhand due to its adaptability to moisture stress conditions. However, its productivity remains considerably low compared to national averages, primarily due to severe weed infestation and lack of effective management practices. The weed flora in this region is highly diverse, comprising grasses, broad-leaved weeds, and sedges, which further complicates management strategies. Despite the availability of general weed management recommendations, region-specific research on integrated weed management practices for Bundelkhand is limited. This gap highlights the need for location-specific studies to develop efficient, economically viable, and sustainable weed management strategies for small and marginal farmers. Therefore, the present study was conducted to evaluate the effectiveness of different integrated weed management practices on weed dynamics, crop growth, yield attributes, productivity, and economic returns of maize under the semi-arid conditions of the Bundelkhand region.

2. Materials and Methods

2.1 Study Area

The field experiment was conducted during the Kharif season of 2025 at the Agricultural Research Farm, Nehru Mahavidyalaya, Lalitpur, Uttar Pradesh, India, located in the Bundelkhand region. The area falls under a semi-arid agro-climatic zone characterized by hot summers, moderate monsoon, and mild winters. The experimental site lies between 24.41°–25.47° N latitude and 78.30°–78.62° E longitude at an elevation of approximately 222–285 m above mean sea level. The region receives an average annual rainfall of about 688 mm, most of which occurs during the southwest monsoon period (June–September). The soil of the experimental field was sandy loam with moderate fertility status (Fig.1).

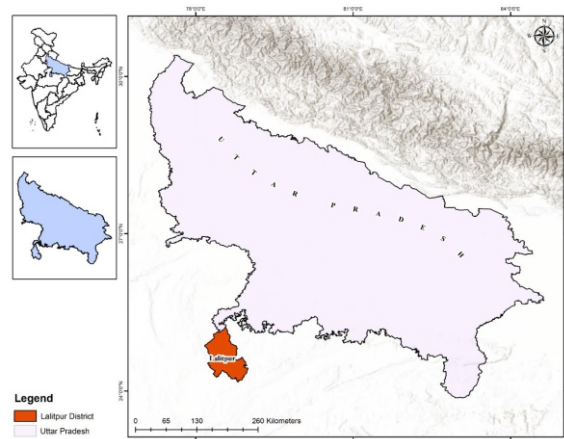


Fig 1: Location map of the experimental site at Nehru Mahavidyalaya, Lalitpur, Jhansi district, Uttar Pradesh, India

2.2 Experimental Design

The experiment was laid out in a Randomized Block Design (RBD) with nine treatments and three replications. The treatments were randomly allocated within each replication to minimize experimental error.

2.3 Treatments

The details of the weed management treatments evaluated in the study are summarized in Table 1.

Table 1: Treatment details of integrated weed management practices in maize

Treatment Code	Treatment Description
T ₁	Weed free
T ₂	Weed check
T ₃	Mulch
T ₄	Atrazine (PE) @ 1 lit/ha
T ₅	2,4-D @ 1 lit/ha at 20 DAS (PoE)
T ₆	Hand weeding at 30 DAS and 60 DAS
T ₇	Atrazine (PE) @ 1 lit/ha fb Hand weeding at 30 DAS
T ₈	Atrazine (PE) @ 1 lit/ha fb 2,4-D at 30 DAS (PoE)
T ₉	Atrazine (PE) @ 1 lit/ha + Hand weeding at 30 DAS + 2,4-D at 60 DAS (PoE)

2.4 Crop Details

Maize hybrid 'HQPM-1' was used as the test crop. Sowing was carried out during the Kharif season following recommended agronomic practices. The crop was sown at a spacing of 60 cm × 20 cm with an appropriate seed rate to maintain optimum plant population. Recommended doses of fertilizers were applied uniformly to all treatments.

2.5 Observations Recorded

Observations were recorded at different growth stages and grouped as follows:

- Weed density (no. m⁻²), weed dry matter (g m⁻²), weed control efficiency (WCE), and weed index (WI).
- Plant population, plant height (cm), number of leaves per plant, and dry matter accumulation.
- Number of cobs per plant, cob length and girth, number of grains per cob, test weight, grain yield, stover yield, and biological yield.
- Cost of cultivation, gross returns, net returns, and benefit–cost (B:C) ratio.

2.6 Statistical Analysis

The experimental data were statistically analyzed using analysis of variance (ANOVA) appropriate for Randomized Block Design as described by Gomez and Gomez (1984).

The significance of treatment effects was tested at the 5% level of probability, and the critical difference (CD) was calculated for comparison of treatment means.

3. Results

3.1 Weed Dynamics

The experimental field was characterized by a heterogeneous and competitive weed flora comprising grasses (*Eleusine indica*, *Digitaria sanguinalis*), broad-leaved weeds (*Amaranthus viridis*, *Commelina benghalensis*), and sedges (*Cyperus rotundus*), reflecting the typical weed spectrum of semi-arid maize systems in the Bundelkhand region. The density and biomass of these weeds varied significantly across treatments, indicating differential effectiveness of weed management strategies. Weed density and dry matter accumulation were significantly reduced under all weed control treatments compared to the weedy check throughout the crop growth period. Among the treatments, the integrated application of atrazine as pre-emergence followed by tembotrione as post-emergence (T_9) consistently recorded the lowest weed density at all observation stages. This reduction was particularly pronounced during the critical period of crop-weed competition, suggesting effective early and sustained weed suppression. The treatment effectively controlled both grassy and broad-leaved weeds, which are typically difficult to manage simultaneously. Weed dry matter accumulation followed a trend similar to weed density, with T_9 registering the minimum biomass production. This indicates not only suppression of weed emergence but also inhibition of weed growth and vigor. Consequently, T_9 achieved weed control efficiency (WCE) exceeding 90%, which was significantly higher than all other treatments except the weed-free condition. The high WCE under T_9 reflects the synergistic effect of combining pre- and post-emergence herbicides, ensuring season-long weed control.

The weedy check recorded the highest weed density and dry matter accumulation, highlighting the severity of weed competition in the absence of control measures. Treatments involving single-method approaches, such as sole herbicide application or manual weeding, were less effective than integrated treatments, indicating the limitations of individual methods in managing complex weed flora. Importantly, the performance of T_9 was statistically comparable to the weed-free treatment, demonstrating that integrated herbicide application can achieve near-complete weed suppression with relatively lower labor inputs. These findings emphasize the importance of integrated approaches in managing diverse weed populations under field conditions (Fig.2).

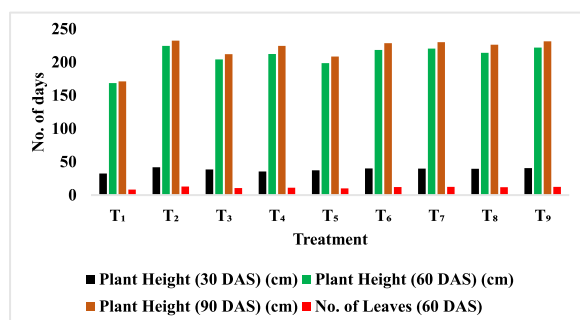


Fig. 2: Effect of Integrated Weed Management Practices on Plant Height and Number of Leaves of Maize at Different Growth Stages

3.2 Crop Growth

Crop growth parameters were significantly influenced by different weed management practices, reflecting the extent of competition between maize and weeds for essential resources. Parameters such as plant height, number of leaves per plant, and dry matter accumulation exhibited clear variations among treatments. The integrated treatment T_9 recorded the maximum plant height throughout the growth period, which was statistically at par with the weed-free treatment. Enhanced plant height under T_9 can be attributed to reduced competition for nutrients, moisture, and light during the early and critical stages of crop growth. The effective suppression of weeds ensured uninterrupted crop growth, resulting in improved vegetative development. Similarly, the number of leaves per plant was significantly higher under T_9 , indicating improved photosynthetic capacity and overall plant vigor. Treatments involving partial weed control showed moderate improvements in leaf production, whereas the weedy check recorded the lowest values due to severe competition stress.

Dry matter accumulation, which is a key indicator of crop growth and productivity, was also significantly higher under integrated weed management treatments. The T_9 treatment recorded the highest biomass accumulation, suggesting efficient resource utilization and enhanced physiological performance. This improvement is likely due to the availability of growth resources exclusively for the crop, resulting from effective weed suppression, the weedy check exhibited poor growth performance across all parameters, highlighting the detrimental effects of unchecked weed competition. The results clearly demonstrate that maintaining a weed-free environment, particularly during the critical growth stages, is essential for achieving optimal crop growth (Fig.3).

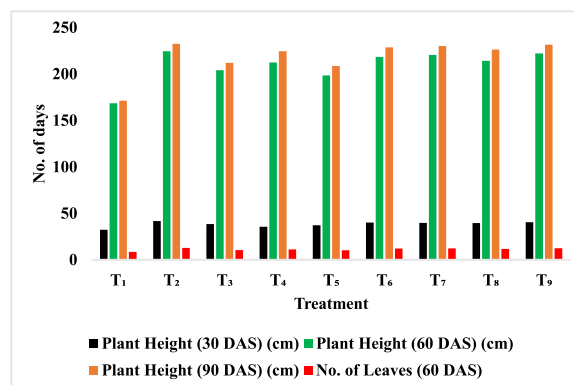


Fig. 3: Effect of Integrated Weed Management Practices on Plant Height and Number of Leaves of Maize at Different Growth Stages

3.3 Yield Attributes and Productivity

Yield attributes and productivity of maize were significantly affected by the different weed management practices. The superiority of integrated weed management treatments was clearly reflected in improved yield components and final productivity. The integrated treatment T_9 recorded significantly higher values for yield attributes such as number of cobs per plant, cob length, cob girth, number of grains per cob, and test weight. These improvements indicate better reproductive development and efficient assimilation of photosynthates.

The enhanced yield attributes under T₉ can be directly linked to reduced crop-weed competition during the critical growth period, allowing the crop to utilize available resources more effectively. Grain yield followed a similar trend, with T₉ recording the highest yield among herbicidal treatments (54.2 q ha⁻¹). This yield was statistically comparable to the weed-free treatment (58.4 q ha⁻¹), indicating that integrated herbicide application can achieve yields close to optimum conditions. The slight numerical difference between T₉ and weed-free treatment may be attributed to minimal residual weed competition or variations in management intensity. Stover yield and biological yield were also significantly higher under T₉, reflecting overall improvement in crop growth and productivity. The harvest index showed a positive trend under integrated treatments, indicating efficient partitioning of assimilates towards grain production. On the other hand, the weedy check recorded the lowest yield and yield attributes due to severe and prolonged weed competition. These results clearly highlight the importance of timely and effective weed management in maximizing crop productivity (Fig.4).

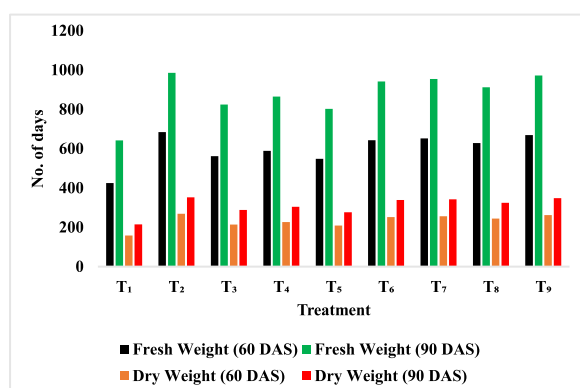


Fig. 4: Effect of Integrated Weed Management Practices on Fresh and Dry Weight of Maize at Different Growth Stages

Table 2: Economic Analysis of Different Weed Management Practices

Treatment Symbols	Cost of Cultivation (Rs./ha)	Gross Returns (Rs./ha)	Net Returns (Rs./ha)	B:C Ratio
T ₁	35,420	52,140	16,720	1.47
T ₂	48,650	134,850	86,200	2.77
T ₉	41,240	125,240	84,000	3.04
SD (±)	1,850	8,420	7,520	0.2
LSD (P=0.05)	5,400	24,580	21,950	0.6

4. Discussion

The present study clearly demonstrated the superiority of integrated weed management (IWM), particularly the sequential application of atrazine (pre-emergence) followed by tembotrione (post-emergence) (T₉), in improving weed control, crop growth, yield, and economic returns in maize under semi-arid conditions. The effectiveness of T₉ can be attributed to its complementary mode of action and its ability to provide season-long weed suppression. The superior performance of T₉ in reducing weed density and dry matter can be explained by the synergistic interaction between pre- and post-emergence herbicides. Atrazine, applied as a pre-emergence herbicide, inhibits photosystem II (PS II) electron transport, thereby preventing early weed establishment by disrupting photosynthesis in germinating weed seedlings [9-10]. This ensures effective control of the first flush of weeds, which is critical for minimizing early crop-weed competition.

3.4 Economic Analysis

Economic evaluation of weed management practices is crucial for assessing their feasibility and adoption by farmers. The analysis revealed significant variation in cost of cultivation, returns, and profitability among treatments. Although the weed-free treatment produced the highest grain yield, it involved substantially higher labor costs due to repeated manual weeding operations. As a result, its economic efficiency was relatively lower compared to integrated treatments. The integrated treatment T₉ recorded the highest net returns and benefit-cost (B:C) ratio of 3.04, making it the most economically viable option among all treatments. The superior profitability of T₉ can be attributed to its ability to achieve high yields comparable to the weed-free treatment while significantly reducing labor costs. This balance between cost and productivity makes integrated weed management particularly suitable for resource-limited farming systems. Other treatments involving single methods showed moderate economic returns, whereas the weedy check resulted in the lowest profitability due to poor yield performance. The findings clearly indicate that integrated weed management not only enhances crop productivity but also improves economic returns, making it a sustainable and farmer-friendly approach (Table 2).

However, pre-emergence herbicides alone are often insufficient to control later-emerging weeds. The subsequent application of tembotrione as a post-emergence herbicide complements this limitation by targeting weeds that escape initial control. Tembotrione belongs to the triketone group and acts by inhibiting the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD), leading to disruption of carotenoid biosynthesis and resulting in bleaching and eventual death of susceptible weeds [11-12]. This dual mechanism ensures broad-spectrum control of both grassy and broad-leaved weeds across different growth stages. Similar findings have been reported by [13-14], who observed that sequential herbicide applications significantly improved weed control efficiency and reduced weed biomass in maize systems. The high weed control efficiency (>90%) observed under T₉ in the present study is consistent with previous reports indicating that integrated herbicide strategies are more effective than single-method approaches [15-16].

Recent studies further confirm that combining herbicides with different modes of action reduces weed escape and delays the development of herbicide resistance, thereby enhancing long-term sustainability [16-17]. Improved weed control under T₉ directly translated into enhanced crop growth parameters such as plant height, number of leaves, and biomass accumulation. This can be attributed to reduced competition for essential growth resources, including nutrients, moisture, and light. Weeds emerging during the early stages of maize growth are particularly competitive due to the slow initial growth of the crop. Effective suppression of weeds during the critical period (20–45 DAS) ensures uninterrupted crop development and improved physiological efficiency [18]. Similar improvements in growth attributes under integrated weed management have been reported by [19]. The enhancement in growth parameters under T₉ was further reflected in improved yield attributes and productivity. Higher values of cobs per plant, grains per cob, and test weight indicate better reproductive development and efficient translocation of assimilates. The grain yield obtained under T₉ (54.2 q ha⁻¹) was statistically comparable to the weed-free treatment, highlighting the effectiveness of integrated herbicide application in achieving near-optimal productivity levels. This finding is in agreement with studies by Mukherjee and Rai (2016) and Kumar et al. (2017), who reported that sequential application of pre- and post-emergence herbicides significantly increased maize yield.

The improved yield under integrated weed management can be explained by the reduction in crop-weed competition during the critical growth period, which allows the crop to utilize available resources more efficiently. In contrast, the weedy check exhibited significantly lower yield due to prolonged competition, which adversely affected both vegetative and reproductive growth stages. These findings are consistent with earlier reports indicating that uncontrolled weeds can reduce maize yield by up to 30–90% depending on infestation intensity [20].

Economic analysis further reinforced the superiority of T₉, which recorded the highest net returns and benefit–cost ratio (3.04). Although the weed-free treatment produced slightly higher yield, its higher labor requirement resulted in increased cost of cultivation, reducing overall profitability. The integrated approach, by combining chemical efficiency with reduced labor dependency, provided an optimal balance between cost and returns. Similar conclusions have been drawn by [17–18], who reported higher economic returns under integrated weed management practices. From a sustainability perspective, the use of herbicides with different modes of action in sequence not only enhances weed control but also reduces the risk of herbicide resistance development. Recent global assessments emphasize that integrated weed management strategies are essential for maintaining long-term productivity and environmental safety in cropping systems [12-13]. Thus, the findings of the present study confirm that the integration of atrazine and tembotrione provides an effective, economically viable, and sustainable approach for managing complex weed flora in maize under semi-arid conditions.

5. Conclusion

The present study demonstrates that integrated weed management (IWM) is markedly superior to single-method approaches in controlling complex weed flora and enhancing maize productivity under semi-arid conditions. Among the treatments, the sequential application of atrazine (pre-emergence) followed by tembotrione (post-emergence) (T₉) proved most effective, achieving high weed control efficiency (>90%) and yields comparable to the weed-free condition. This treatment also recorded the highest economic returns with a benefit–cost ratio of 3.04, indicating strong profitability. The results highlight that effective weed suppression during the critical period significantly improves crop growth and yield. Therefore, the T₉ treatment is recommended as a sustainable and economically viable weed management strategy for maize cultivation in the Bundelkhand region, particularly for resource-limited farmers.

6. Recommendations

Based on the findings of the present study, the integrated application of atrazine (pre-emergence) followed by tembotrione (post-emergence) is recommended for effective weed management in maize under the semi-arid conditions of the Bundelkhand region. This approach ensures season-long weed control, enhances crop productivity, and maximizes economic returns. Farmers should adopt this strategy particularly during the critical crop–weed competition period (20–45 DAS) to minimize yield losses. Additionally, integrating herbicides with different modes of action is advised to delay the development of herbicide resistance and ensure long-term sustainability. For small and marginal farmers, this method offers a cost-effective alternative to labor-intensive manual weeding. Further research may focus on integrating this approach with cultural practices such as mulching and crop rotation for improved ecological resilience.

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