Turkish Journal of Agriculture - Food Science and Technology, 12(s1): 1997-2008, 2024
DOI: https://doi.org/10.24925/turjaf.v12is1.1997-2008.6865

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Weed Management Effects on Weed Dynamics, Yield and Economics of Spring Maize at Dang, Nepal

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A R T I C L E I N F O

Research Article

Received : 15.05.2024
Accepted : 07.08.2024

Keywords:
Weed
Spring maize
Atrazine
Tembotrione
Yield

A B S T R A C T

Weeds pose a significant challenge in maize fields in the Dang district, leading to a substantial 52% reduction in yield. Hence, this study was conducted in Satbariya village of Dang, Nepal, in 2023 to evaluate the impact of various weed management practices on weed dynamics, growth, and yield of spring maize. The experiment included seven treatments: a weedy check, weed-free plot, pre-emergence application of atrazine at 1.25 a.i. kg/ha (AtPrE), post-emergence application of atrazine at 1.25 a.i. kg/ha (AtPoE), manual weeding at 30 DAS, mini-tiller at 30 DAS, and LaPoE (tembotrione 42% SC + atrazine 50% WP) applied as post-emergence. The Subarna variety of maize was chosen for the study. Fifteen weed species from seven different families were identified in the experimental area. Specific morphological and phenological parameters, such as plant height and days to tasseling and silking, were not significantly influenced by the weed control methods. However, significantly lower weed density and biomass were observed in the weed-free plot and LaPoE. Similarly, weed-free plots and LaPoE exhibited significantly higher weed control efficiency (WCE) and weed control index at both 45 and 60 DAS, leading to a lower weed index (0.00–16.71%) and more effective weed control. Concerning the yield parameters, cob length, number of kernels per row, and 1000-grain weight were significantly higher in weed-free plots, followed by LaPOE, and the highest grain and biological yield were observed in weed-free plot (6.14–15.18 tons/ha) and LaPoE (5.12–13.32 tons/ha). Moreover, the benefit-cost ratio and net return were observed to be highest with LaPoE. This study suggests that LaPoE can be an effective and economical weed management strategy for increasing maize yield and profitability. Further research could explore the long-term effects of using LaPoE on weed control and crop productivity.

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Introduction

Maize (Zea mays L.) is a significant cereal crop with a high photosynthetic potential, making it adaptable to a wide range of environments (Thakur et al., 2020). It is a member of the grass family, Poaceae, and is the third most important cereal crop globally, after wheat and rice (Swaroop & David, 2021). It has 66.3% carbohydrates, 11.1% protein, 3.6% fat, 2.7% fiber, 1.5% minerals (calcium, phosphorus, iron), and 1.5% vitamins (A, B, and E). It continues to be a staple in the diet of many because of its nutritional value, and the rapid growth of Nepal's poultry and feed industries is contributing to the increasing demand (Timsina et al., 2019).

In Nepal, 985,565 hectares were planted with maize, producing 3,106,397 metric tons at a productivity rate of 3.15 metric tons per hectare (MoALD, 2022). This productivity is significantly lower than the achievable yield of 5.7 metric tons per hectare, as reported by Timsina et al. (2019). Despite the vast marketing potential, the accelerated rate of demand growth outpaces the increase in maize output due to factors such as inadequate production capacity and distribution inefficiencies, leading to a substantial disparity between maize output and demand (Dhakal et al., 2022).

Several factors contribute to the gap between maize demand and the supply chain, including weed infestation, soil fertility decline, climatic uncertainty, and the subsistence farming approach. Among these, weed infestation is a major concern. Wide spacing between maize rows, frequent irrigation, and heavy use of chemical fertilizers create favorable conditions for weed development and establishment, leading to increased yield loss (Shrestha et al., 2021). This situation is further exacerbated in Sadbariya, Dang, due to inappropriate weed management practices adopted by farmers.

Farmers often remain unaware that understanding the critical weed infestation period is essential for successful maize cultivation. They typically prefer manual weeding methods over other techniques, which leaves them unaware of alternative methods that could be more cost-effective and productive. Studies have identified the critical weed infestation period to be between 2 to 8 weeks after sowing, specifically from the third to fifth leaf tip stages of development (Duwadi et al., 2021; Cerrudo et al., 2012). During this period, weed interference can lead to increased plant-to-plant variability, reduced grain yield, and a higher incidence of bareness (Cerrudo et al., 2012). Employing non-chemical weed management strategies, including mechanical, biological, and cultural methods, during this critical period can effectively suppress weed populations and improve economic returns (Duwadi et al., 2021).

Jain (2022) observed that maintaining weed-free conditions significantly enhances maize growth and yield. Similarly, Khan et al. (2013) and Abimbola (2019) documented the effectiveness of various weed control methods, such as pre-emergence herbicides, hoe-weeding, and mulching, in suppressing weed growth and enhancing maize yield. Singh et al. (2021), BB et al. (2021) and O.S. et al. (2021) reported a significant reduction in weed density and dry matter, as well as a superior maize yield with the use of atrazine.

Idziak & Woznica (2014) found that the post-emergence application of tembotrione, particularly when combined with a surfactant, effectively controlled weeds and increased grain yield. Sharma et al. (2023) reported that the combined application of tembotrione and atrazine was more effective in controlling weeds and increasing maize yield compared to the sole application of tembotrione. A combination of hoeing and herbicides has been found to increase maize yield and its components significantly, while also effectively controlling weeds (Khatam et al., 2013; Soliman & Hamz, 2014).

The objective of this study is to address weed infestation in maize farming, which significantly negatively impacts crop productivity. The study aims to examine the prevalent weed population and how different weed management practices affect weed dynamics, growth, phenology, yield attributes, and the economic aspects of maize cultivation. Understanding the prevalence and effects of various weeds on the maize crop is crucial for informed decision-making and effective cultivation strategies. Furthermore, the evaluation of various weed management practices will help to identify the most cost-effective and productive approaches. Therefore, farmers will be empowered to improve their current practices.

Materials and methods

Location and Site Weather and Soil Properties

A field experiment was conducted in Lamahi Municipality-8, Satbariya, Dang, Nepal, which falls under the PMAMP superzone of Maize, Lamahi. The experimental site is situated at an altitude of 629 meters above sea level. Figures 1 and 2 present information on the climatic conditions during the study's duration and the location of the experimental area, respectively.

Plant Material and Experimental Design

The seeds of the Subarna variety were utilized for this experimental study. The field was thoroughly plowed and leveled one week prior to planting. Seeds were sown on February 26, 2023, with a row-to-row spacing of 60 cm and a plant-to-plant spacing of 20 cm. During field preparation, well-decomposed farmyard manure (20 tons ha^{-1}) was mixed with the soil. A full dose of DAP (60 kg ha^{-1}) and MOP (40 kg ha^{-1}) was applied as a basal dose at planting. Half of the urea dose (180 kg ha^{-1}) was incorporated during field preparation, with the remaining half applied in split doses at the knee-high and tasseling stages. The first irrigation was carried out immediately after planting, followed by subsequent irrigations every 6–7 days, adjusted based on rainfall and soil moisture levels.

The experiment was conducted using a Randomized Block Design (RCBD) with ten treatments, each replicated three times. Each experimental plot measured 12 m², with dimensions of 4 m by 3 m, and consisted of five rows with 20 plants per row. The total research area covered was 362.25 m², with inter-plot spacing of 60 cm, block-to-block spacing of 75 cm, and a border width of 30 cm. Details of the treatments used in the experiment are provided in Table 1.

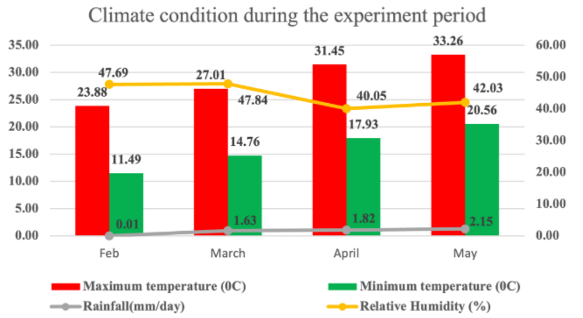

Figure 1. The climatic condition of the experimental area
Data Source: (POWERNASA, 2023)

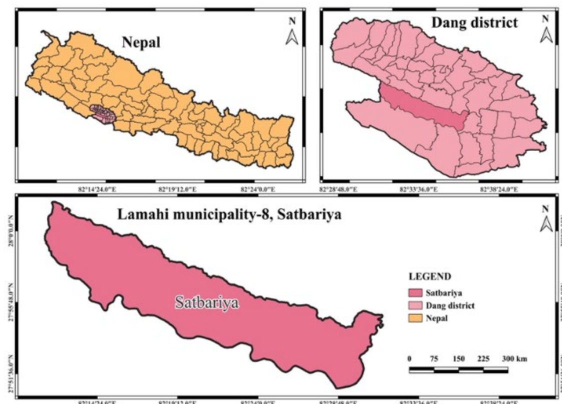

Figure 2. Location of the experimental field.
(Created by using QGIS 10.8 software)

Table 1. Treatment details

Treatments	Trade name	Chemical name	Dose	Application time
T1: Weedy check	-	-	-	No weed control
T2: Weed-free	-	-	-	Weeding at 7-10 days interval
T3: Atrazine as pre-emergence (AtPrE)	Foost	Atrazine 50% WP	1.25 a.i. kg/ha (Nadiger et al., 2013)	Applied at 2 DAS
T4: Atrazine as post-emergence (AtPoE)	Foost	Atrazine 50% WP	1.25 a.i. kg/ha (Nadiger et al., 2013)	Applied at 30 DAS
T5: Tembotrione as post-emergence (LaPoE)	Laudis	(Tembotrione 42% SC + surfactant)	120gm a.i/ha Tembotrione + 1000ml/ha surfactant (Horowitz et al., 1990) + 0.6 a.i. kg/ha atrazine 50% WP (Sharma et al., 2018)	Applied at 30 DAS
T6: Mini tiller	-	-	-	Applied at 30 DAS
T7: Manual Weeding	-	-	-	Applied at 30 DAS

Note: WP: wettable powder; SC: soluble concentrate; DAS: days after sowing; a.i.: active ingredient; kg/ha: Kilograms per hectare, ml/ha: milli liters/hectare, gm/ha: grams per hectare

Data Collection and Observation

Weed dynamics parameters

To assess the impact of weed management practices on weed dynamics, various observations including weed flora, density, dry weight, weed control efficiency (WCE) (equation 1), and weed control index (WCI) (equation 2) were conducted. Quadrants measuring 0.5 m² (0.5 m × 1 m) were established at four distinct locations within each plot to monitor weed parameters. The weed flora within each quadrant was identified with the help of online resources and experts, and categorized into three groups: sedge, broadleaf, and narrow-leaf weeds, based on their morphological characteristics. The total weed count for each quadrant was recorded and expressed as the number of weeds per square meter. For dry weight measurement, the weeds were sun-dried and subsequently oven-dried at 72°C for 3 days. Dry weight and weed count data were collected separately for sedges, broadleaf, and narrow-leaf weeds at 30, 45, and 60 days after sowing (DAS). Weed control efficiency was calculated as the percentage reduction in weed population due to weed management practices compared to the control (weedy check). The weed control index was determined by comparing the dry weight of weeds from different treatments to that from the control plot.

$$\mathrm{WCE} = \frac{(\mathrm{WPWC}-\mathrm{WPTP})}{\mathrm{WPWC}} \times 100 \quad (1)$$

WCE : Weed control efficiency (%)
WPWC : Weed population(no/m^2) in weedy check
WPTP : weed population(no/m^2) in treated plot
(Mishra et al., 2020)

$$\mathrm{WCI} = \frac{(\mathrm{DMPWC}-\mathrm{DMPTP})}{\mathrm{DMPWC}} \times 100 \quad (2)$$

WCI : Weed control index (%)
DMPWC : Dry matter production (g) in weedy check
DMPTP : Dry matter production (g) in treated plot
(Mishra et al., 2020)

$$\mathrm{WI} = \frac{(\mathrm{TYWFC}-\mathrm{TYST})}{\mathrm{TYWFC}} \times 100 \quad (3)$$

WI : Weed index
TYWFC : Total yield from weed free check
TYST : Total yield from specific treatment
(Mishra et al., 2020)

Biometrical and Phenological Parameters of Maize

Plant height was measured from 10 randomly selected plants in each plot at 30, 45, 60, 75, and 90 days after sowing (DAS) at 15-day intervals. Phenological observations were recorded at the tasseling and silking stages, corresponding to 50% and 100% completion, respectively, and noted as Days After Sowing (DAS).

Yield Attributing Parameters of Maize

The maize crops were harvested on June 14, 2023. To evaluate yield parameters, measurements were taken for the number of kernels per ear, cob length (cm), cob girth (mm) (equation 4), 1000-grain weight (g), shelling percentage (equation 5), sterility percentage (equation 6), grain yield (kg/ha) (equation 7), and harvest index (equation 8) from ten maize plants per plot.

$$\text{Cob girth (mm)} = \frac{\text{Circumference of the girth}}{3.14} \quad (4)$$

$$\text{Shelling Percentage (\%)} = \frac{\text{Grain yield}}{\text{Cob yield}} \times 100 \quad (5)$$

(Adhikari et al., 2023)

$$\text{Sterility Percentage} = \frac{\mathrm{LUGC}}{\mathrm{TLC}} \times 100 \quad (6)$$

LUGC : Length of unfilled grain in cob
TLC : Total length of the cob
(Adhikari et al., 2023)

$$GY = \frac{(100-MC) \times PY \times 1000}{84 * \text{net plot area } (m^2)} \quad (7)$$

GY : Grain yield (kg/ha)
MC : Moisture content
PY : Plot yield(kg)
(Adhikari et al., 2023)

$$\text{Harvest index } (\%) = \frac{\text{Grain yield}}{\text{Biological yield}} * 100 \quad (8)$$

(Adhikari et al., 2023)

Economic Analysis

Gross monetary return (NPR) is the entire monetary worth of the economic products and byproducts produced from the crop grown under the different treatments (equation 9); this value was determined using local market prices. Cost of cultivation (NPR) included fixed costs (land lease) and variable costs (labor, a hired miner, the cost of seeds, manures, fertilizers, pesticides, and herbicides, as well as the charges for irrigation, harvesting, drying, and transportation) incurred during maize cultivation. It was estimated using the local charges. Net return (NPR) was determined by deducting cultivation costs from gross returns (equation 10). The benefit-cost ratio (BCR) measures the relationship between the gross return and the cost of cultivation for a specific treatment (equation 11). This index calculates the advantage a farmer receives in exchange for the cost of adopting a specific treatment.

$$GR = TMY \times SPM \quad (9)$$

GR : Gross return
TMY: Total marketable yield
SPM : Selling price of maize

$$NR = \text{Gross return} - \text{total cost of production} \quad (10)$$

NR: Net returns

$$\text{Benefit} - \text{cost ratio} = \frac{\text{Net return}}{\text{Total cost of production}} \quad (11)$$

Data Analysis

The data was systematically organized, with treatments applied across four replicates and various parameters measured. Statistical analysis was conducted using MS Excel and R-Studio. Variances were analyzed, and mean values of individual parameters were compared using Duncan's Multiple Range Test (DMRT) at a significance level of $p<0.05$. The results were thoroughly analyzed and discussed in relation to existing literature.

Results

Weed Species

Table 2 revealed that fifteen different weed species belonging to seven different families were found in the experimental field. *Cyperus rotundus, Cyperus esculentus, and Argemone Mexicana* were major weed species identified in the field. The population of sedges was significantly higher than that of dicots and monocots. According to Shrestha et al. (2021), sixteen distinct weed species from six different families were also reported at Dhading Besi, Nepal. The most common weed species found in the study area were *Digitaria spp., Fimbristylis spp., Cynodon dactylon, Ageratum conyzoides, Oryza sativa, Digitaria album, Cyperus rotundus, and Stellaria media*, according to Shrestha et al. (2021).

Weed Density

Weed control methods significantly influenced weed density, which was consistently observed to be lower in weed-free plots and greater under weedy check at all observations (Table 3). After weed-free, post-emergence application of AtPrE resulted in the lowest weed density across all three weed categories at 30 DAS. Conversely, the post-emergence application of Tembotrione resulted in the lowest weed density across all three weed categories at 45 and 60 DAS following the weed-free. A similar trend was observed in total weed density, with the lowest value recorded after the post-emergence application of atrazine at 30 DAS and the post-emergence application of Tembotrione at 45 and 60 DAS.

Table 2. Weed species observed in the experimental plots of spring maize at Dang, Nepal

Common name	Scientific name	Family
Grasses		
Bermuda grass	*Cynodon dactylon*	Poaceae
Cockspur	*Echinochloa crusgalli*	Poaceae
Signal grass	*Brachiaria repens*	Poaceae
Fountain grass	*Pennisetum cenchroides*	Poaceae
Egyptian crowfoot grass	*Dactyloctenium aegyptium*	Poaceae
Hairy crabgrass	*Digitaria sanguinalis*	Poaceae
Dicots		
Parthenium	*Parthenium hysterophorus*	Asteraceae
Indian nettle	*Acalypha indica*	Euphorbiaceae
Mexican prickly poppy	*Argemone Mexicana*	Papaveraceae
Hemp	*Cannabis sativa*	Cannabaceae
Billygoat weed	*Ageratum conyzoides*	Asteraceae
Ballon cherry	*Physalis angulate*	Solanaceae
Sedges		
Purple nutsedge	*Cyperus rotundus*	Cyperaceae
Yellow nutsedge	*Cyperus esculentus*	Cyperaceae
Rice flat sedge	*Cyperus iria*	Cyperaceae

Table 3. Weed density as influenced by different weed management practices at Dang, Nepal in 2023

Weed management practices	Weed Density (no/m^2)			
	30 DAS			
	SW	GW	BW	Total
Weed free	0.71^{c} (0.00)	0.71^{d} (0.00)	0.71^{b} (0.00)	0.71^{c} (0.00)
Manual weeding	16.17^{a} (272.00)	6.38^{a} (41.33)	7.51^{a} (56.00)	18.99^{a} (369.33)
AtPrE	9.52^{b}(94.00)	2.59^{cd}(8.00)	2.59^{b}(8.00)	10.34^{b}(110.00)
AtPoE	17.44^{a}(306.67)	5.53^{ab}(32.67)	5.57^{a}(30.67)	19.19^{a}(370.00)
LaPoE	20.04^{a}(450.00)	3.89^{abc}(15.33)	7.11^{a}(54.00)	22.17^{a}(519.33)
Mini Tiller	17.98^{a}(332.67)	3.15^{bc}(14.67)	6.27^{a}(40.00)	19.47^{a}(387.33)
Weedy check	17.55^{a}(309.33)	4.84^{abc}(25.33)	6.74^{a}(46.00)	19.48^{a}(380.67)
F-test (α=0.05)	S***	S**	S***	S***
SEM (±)	2.07	0.75	0.73	1.71
LSD (α=0.05)	6.39	2.33	2.24	5.27
CV (%)	25.30	33.81	24.12	17.79
Weed management practices	Weed Density (no/m^2)			
	45 DAS			
	SW	GW	BW	Total
Weed free	0.71^{d}(0.00)	0.71^{d}(0.00)	0.71^{e}(0.00)	0.71^{d}(0.00)
Manual weeding	14.27^{b}(204.00)	3.97^{ab}(16.00)	5.63^{b}(31.33)	15.84^{b}(251.33)
AtPrE	13.78^{bc}(197.33)	2.50^{c}(6.67)	2.95^{cd}(10.67)	14.49^{b}(214.67)
AtPoE	16.00^{b}(256.00)	4.98^{a}(26.67)	4.72^{bc}(22.00)	17.44^{b}(304.67)
LaPoE	10.71^{c}(115.33)	1.00^{d}(0.67)	2.45^{de}(6.00)	11.03^{c}(122.00)
Mini Tiller	14.76^{b}(222.67)	2.68^{bc}(7.33)	5.07^{b}(25.33)	15.83^{b}(255.33)
Weedy check	21.55^{a}(466.00)	4.70^{a}(22.00)	8.25^{a}(68.67)	23.57^{a}(556.67)
F-test (α=0.05)	S***	S***	S***	S***
SEM (±)	1.09	0.43	0.58	1.01
LSD (α=0.05)	3.38	1.32	1.78	3.11
CV (%)	14.52	25.21	23.52	12.36
Weed management practices	Weed Density (no/m2)			
	60 DAS			
	SW	GW	BW	Total
Weed free	0.71^{a}(0.00)	0.71^{c}(0.00)	0.71^{d}(0.00)	0.71^{e}(0.00)
Manual weeding	20.49^{ab}(429.33)	3.72^{abc}(15.33)	5.47^{bc}(30.00)	21.56^{abc}(474.67)
AtPrE	16.63^{bc}(293.33)	3.28^{bc}(15.33)	6.43^{bc}(42.67)	18.17^{c}(351.33)
AtPoE	17.53^{ab}(311.33)	5.59^{ab}(31.33)	7.79^{b}(60.67)	20.02^{bc}(403.33)
LaPoE	12.74^{c}(170.00)	0.71^{c}(0.00)	3.63^{cd}(11.33)	13.17^{d}(181.33)
Mini Tiller	21.16^{a}(458.00)	6.39^{ab}(47.33)	4.99^{bc}(31.33)	23.07^{ab}(536.67)
Weedy check	21.77^{a}(476.00)	6.96^{a}(53.33)	10.84^{a}(118.00)	25.42^{a}(647.33)
F-test (α=0.05)	S***	S**	S***	S***
SEM (±)	1.31	1.08	0.94	1.28
LSD (α=0.05)	4.03	3.32	2.89	3.94
CV (%)	14.27	47.84	28.77	12.69

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; data are subjected to square root transformation $\sqrt{(x + 0.5)}$ and data on parentheses are original values; DAS: days after sowing; S*:significant at 5% probability level; S**: significant at 1% probability level; S***: significant at 0.1% probability level; SW: sedge weight; GW: grass weight; BW: broadleaf weight; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence; no/m^2: number per square meter

Weed Dry Weight

Weed dry weight was significantly influenced by weed control methods (Table 4). Weed-free plots consistently resulted in the lowest sedge, broadleaf, and grassy weed dry weight at all stages of observation. At 30 DAS, LaPoE exhibited the highest sedge and broadleaf weed dry weight, while the lowest was observed in AtPoE after weed-free treatment. Conversely, LaPoE resulted in the lowest dry weight across all three weed categories after weed-free at 45 and 60 DAS and was statistically similar to AtPrE. The lowest dry weight in all three weed categories was observed in weedy check plots at 45 and 60 DAS. A similar trend was observed in total weed dry weight. The highest dry weight was observed in the weedy check at all stages of observation, statistically similar to manual tillering at 30 and 60 DAS. Conversely, the lowest total weed dry weight was observed under AtPrE at 30 DAS and under LaPoE at 45 and 60 DAS after weed-free.

Weed Control Efficiency, Weed Control Index, and Weed Index

Weed control methods significantly influenced weed control efficiency, weed control index, and weed index (Table 5). Weed-free consistently resulted in the highest weed control efficiency and weed control index at 45 and 60 DAS, in contrast to the lowest values observed under the weedy check. After the weed-free method, LaPoE resulted in higher weed control efficiency at 45 and 60 DAS. A similar trend was observed in the weed control index with LaPoE which was statistically similar to AtPrE at 60 DAS. The lowest value for weed index was observed in weed-free check (0.00), which was statistically similar to LaPoE (16.7). In contrast, the highest value for weed index was reported in the weedy check (51.61), which was statistically similar to mini tiller (35.88) and manual weeding (33.84).

Plant Height

There was no significant effect of the weed control method on plant height (Table 6). However, the weed-free plot exhibited maximum plant height at all stages of observation except at 60 DAS, when LaPoE resulted in maximum plant height. Conversely, a weedy check resulted in the minimum plant height, followed by a mini tiller at all stages of observation.

Days to Tasselling and Silking

There was no significant influence of the weed control method on phenological attributes such as days to tasseling and silking (Table 7). However, the weed-free plot exhibited the shortest duration to reach 50% tasseling and 100% tasseling, followed by the LaPoE treatment. Conversely, the longest duration to achieve 50% tasseling and 100% tasseling was observed in the manual weeding treatment, followed by the weedy check treatment. A similar pattern was noted for the duration to achieve 50% silking and 100% silking, with the shortest duration in the weed-free treatment and the longest duration in the manual weeding treatment.

Table 4. Weed dry weight as influenced by different weed management practices at Dang, Nepal in 2023

Weed management practices	Weed Dry Weight (g/m2)			
	30 DAS			
	SW	GW	BW	Total
Weed free	0.71^{c}(0.00)	0.71(0.00)	0.71^{d}(0.00)	0.71^{d}(0.00)
Manual weeding	5.52^{a}(30.67)	3.63(13.00)	2.91^{bc}(8.67)	7.26^{b}(52.33)
AtPrE	3.16^{b}(10.67)	2.22(5.67)	1.92^{cd}(4.00)	4.44^{c}(20.33)
AtPoE	6.24^{a}(38.67)	2.94(8.33)	3.41^{abc}(11.67)	7.65^{b}(58.67)
LaPoE	6.79^{a}(47.67)	2.77(8.00)	4.95^{a}(25.33)	9.01^{a}(81.00)
Mini Tiller	6.42^{a}(42.33)	2.18(5.33)	4.38^{ab}(20.67)	8.29^{ab}(68.33)
Weedy check	6.36^{a}(40.33)	3.31(12.00)	4.50^{ab}(21.00)	8.56^{ab}(73.33)
F-test (α=0.05)	S***	NS	S**	S***
SEM (±)	0.59	0.58	0.59	0.41
LSD (α=0.05)	1.82	1.79	1.83	1.25
CV (%)	20.31	39.72	31.68	10.73
Weed management practices	Weed Dry Weight (g/m2)			
	45 DAS			
	SW	GW	BW	Total
Weed free	0.71^{d}(0.00)	0.71^{d}(0.00)	0.71c(0.00)	0.71^{e}(0.00)
Manual weeding	4.62^{bc}(21.00)	2.8^{a}(7.33)	2.41b(5.67)	5.87^{bc}(34.00)
AtPrE	4.77^{bc}(23.67)	1.59^{bc}(2.33)	2.53b(6.00)	5.61^{cd}(32.00)
AtPoE	5.51^{ab}(30.00)	3.11^{a}(10.00)	3.15^{b}(10.00)	7.09^{b}(50.00)
LaPoE	3.74^{c}(14.00)	0.81^{cd}(0.17)	2.21^{b}(4.67)	4.31^{d}(18.83)
Mini Tiller	4.78^{bc}(22.33)	1.76b(2.67)	3.42^{b}(11.33)	6.06^{bc}(36.33)
Weedy check	6.56^{a}(42.67)	2.61^{a}(6.33)	5.55^{a}(31.33)	8.97^{a}(80.33)
F-test (α=0.05)	S***	S***	S***	S***
SEM (±)	0.40	0.27	0.39	0.43
LSD (α=0.05)	1.24	0.80	1.19	1.33
CV (%)	15.88	24.71	23.47	13.52
Weed management practices	Weed Dry Weight (g/m2)			
	60 DAS			
	SW	GW	BW	Total
Weed free	0.71^{c}(0.00)	0.71^{c}(0.00)	0.71^{d}(0.00)	0.71^{e}(0.00)
Manual weeding	7.92^{a}(65.33)	2.50^{abc}(6.67)	3.95^{bc}(15.67)	9.19^{bc}(87.67)
AtPrE	5.43^{b}(31.67)	1.97^{bc}(4.33)	3.75^{bc}(13.67)	6.91^{cd}(49.67)
AtPoE	6.55^{ab}(44.00)	4.37^{a}(18.67)	3.36^{bc}(11.00)	8.51^{bc}(73.67)
LaPoE	4.19^{b}(17.33)	0.71^{c}(0.00)	2.16^{cd}(4.67)	4.68^{d}(22.00)
Mini Tiller	8.45^{a}(73.67)	3.78^{ab}(16.33)	5.26^{b}(29.00)	10.91^{ab}(119.00)
Weedy check	8.02^{a}(64.00)	3.97^{ab}(17.00)	8.11^{a}(67.00)	12.16^{a}(148.00)
F-test (α=0.05)	S***	S**	S***	S***
SEM (±)	0.76	0.62	0.58	0.77
LSD (α=0.05)	2.33	1.92	1.80	2.38
CV (%)	22.23	42.00	25.96	17.64

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; data are subjected to square root transformation $\sqrt{(x + 0.5)}$ and data on parentheses are original values; DAS: days after sowing; NS: non-significant; S*:significant at 5% probability level; S**: significant at 1% probability level; S***: significant at 0.1% probability level; SW: sedge weight; GW: grass weight; BW: broadleaf weight; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence; g/m^2: grams per square meter

Table 5. Weed control efficiency, weed control index, and weed index as influenced by different weed management practices of spring maize at Dang, Nepal in 2023

Weed Management Practices	Weed Control Efficiency (WCE)		Weed Control Index (WCI)		Weed Index (WI)
	45 DAS	60 DAS	45 DAS	60 DAS	
Weed free	96.98[a]	97.20[a]	92.04[a]	94.14[a]	0.00[c]
Manual weeding	32.58[c]	15.58[cde]	34.21[c]	24.65[cd]	33.84[ab]
AtPrE	38.75[c]	29.26[c]	36.63[c]	43.16[bc]	26.99[b]
AtPoE	25.78[c]	21.33[cd]	20.9[c]	29.16[cd]	30.2[ab]
LaPoE	52.90[b]	48.65[b]	52.41[b]	61.01[b]	16.7[bc]
Mini tiller	32.78[c]	9.29[de]	31.96[c]	10.04[de]	35.88[ab]
Weedy Check	0.00[d]	0.00[e]	0.00[d]	0.00[e]	51.61[a]
F-test (α=0.05)	S***	S***	S***	S***	S**
SEM (±)	4.23	4.92	4.81	6.18	6.79
LSD (α=0.05)	13.03	15.15	14.84	19.04	20.93
CV (%)	18.33	26.95	21.77	28.57	42.20

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; DAS: days after sowing; SEM: standard error of mean; LSD: Least significant difference; CV: coefficient of variation; S*:significant at 5% probability level; S**: significant at 1% probability level; S***: significant at 0.1% probability level; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence

Table 6. Plant height as influenced by different weed management practices of spring maize at Dang, Nepal in 2023

Weed Management Practices	Plant height (cm)			
	30 DAS	45 DAS	60 DAS	90 DAS
Weed free	23.77	45.55	98.55	195.79
Manual weeding	22.42	40.81	91.38	177.57
AtPrE	23.42	40.86	97.45	187.69
AtPoE	22.75	40.83	90.35	177.58
LaPoE	22.47	44.63	101.24	191.71
Mini tiller	21.54	40.09	84.18	176.38
Weedy Check	21.29	36.71	83.52	170.89
F-test (α=0.05)	NS	NS	NS	NS
SEM (±)	1.56	2.66	8.14	6.38
LSD (α=0.05)	4.81	8.19	25.08	19.67
CV (%)	11.99	11.14	15.26	6.06

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; DAS: days after sowing; NS: non-significant; SEM: standard error of mean; LSD: Least significant difference; CV: coefficient of variation; NS: Non-significant; S*:significant at 5% probability level; S**: significant at 1% probability level; S***: significant at 0.1% probability level; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence; cm: centimeters

Table 7. Days to tasselling and silking as influenced by different weed management practices of spring maize at Dang, Nepal in 2023

Weed Management Practices	Days to 50% Taselling	Days to 100% Taselling	Days to 50% Silking	Days to 100% Silking
Weed free	76.67	79.33	80.67	82.67
Manual weeding	78.67	81	83	86
AtPrE	77.67	80.33	82	84
AtPoE	77.33	80	81.67	84
LaPoE	77	79.67	80.67	83.33
Mini tiller	77.67	80.67	82	84.33
Weedy Check	78	80.67	82.33	84.67
F-test (α=0.05)	NS	NS	NS	NS
SEM (±)	0.89	0.96	0.84	0.94
LSD (α=0.05)	2.75	2.95	2.59	2.90
CV (%)	1.99	2.06	1.78	1.93

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; NS: non-significant; SEM: standard error of the mean; LSD: Least significant difference; CV: coefficient of variation; S*:significant at 5% probability level; NS: Non-significant; S**: significant at 1% probability level; S***: significant at 0.1% probability level; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence

Yield Attributing Characters

There was no statistically significant influence of weed control methods on the number of cobs harvested per m^2, cob girth, and number of rows/cobs. However, maximum values for these parameters were observed at weed-free plots, followed by AtPrE for cob harvested/ m^2, and LaPoE for cob girth and the number of rows/cobs. Conversely, the lowest number of cobs harvested per m^2 was observed at the mini-tiller plots. followed by AtPoE. The minimum values for cob girth and the number of rows per cob were observed at the weedy check plots, followed by the manual weeding plots.

Cob length, number of kernels per row, and thousand-grain weight were significantly influenced by weed control methods (Table 8). The highest cob length (15.83 cm) was observed at the weed-free plot, followed by LaPoE (14.79cm). In contrast, the lowest cob length (13.05 cm) was noted at the weedy check plot, followed by mini tiller (13.35 cm). The highest value for the number of kernels per row was noted at the weed-free plot (32.07) followed by LaPoE (29.92 cm). Conversely, the lowest value for the same parameter was recorded at the weedy check plot (23.47), followed by the mini tiller plot (26.13). The highest value for thousand-grain weight was found to be 248.33g and 234.33g at LaPoE and weed-free, respectively. Conversely, the lowest values for thousand-grain weight were found to be 171.67g and 187.33g at weedy check and mini-tiller plots, respectively.

Grain Yield, Harvest Index, Shelling Percentage, and Sterility Percentage

Weed control methods significantly influenced the yield parameters of maize except for the harvest index (Table 9). Weed-free plots and LaPoE plots achieved maximum grain yield (6.14-5.12 tons/ha) and biological yield (15.18–13.32 tons/ha). Conversely, weedy check and mini tiller plots reported minimum grain yield (2.96-3.89 tons/ha) and biological yield (9.13-10.82 tons/ha).

The maximum shelling percentage was observed at weed-free (80.77%) and LaPoE (79.14%), whereas the minimum shelling percentage was recorded at weedy check (77.55%) and manual weeding (77.732%). In terms of sterility percentage, higher values were noted at the weedy check plot (20.69%) and mini tiller plot (18.33%), while lower values were observed at weed-free (14.27%) and LaPoE (16.52%).

Economic Analysis of Maize Cultivation

The economic parameters of maize cultivation significantly varied with weed control methods (Table 10). LaPoE plot had the highest B: C ratio and gross return, indicating a strong financial performance. Although the gross return is higher with weed-free management, the net return and B: C ratio were lower due to the increased costs associated with this method.

Table 8. Yield attributing characters as influenced by different weed management practices of spring maize at Dang, Nepal in 2023

Weed Management Practices	No.of cob harvested/m^2	Cob Length	Cob Girth	No. of rows/cob	No. of kernels/row	Thousand Grain Weight
Weed free	7.92	15.83^{a}	14.09	14.53	32.07^{a}	234.33^{ab}
Manual weeding	7.73	13.99^{bcd}	13.48	13.87	27.73^{b}	200.67^{cd}
AtPrE	7.78	14.72^{b}	13.8	14.13	28.20^{ab}	208.00^{bc}
AtPoE	7.55	14.09^{bc}	13.59	14.13	26.67^{bc}	203.33^{bcd}
LaPoE	7.73	14.79^{b}	13.83	14.67	29.2^{ab}	248.33^{a}
Mini tiller	7.36	13.35^{cd}	13.63	13.87	26.13^{bc}	187.33^{cd}
Weedy Check	7.69	13.05^{d}	13.32	13.33	23.47^{c}	171.67^{d}
F-test (α=0.05)	NS	S***	NS	NS	S*	S**
SEM (±)	0.27	0.30	0.33	0.51	1.28	9.92
LSD (α=0.05)	0.83	0.94	1.03	1.59	3.95	30.58
CV (%)	6.10	3.71	4.24	6.34	8.04	8.28

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; NS: non-significant; SEM: standard error of the mean; LSD: Least significant difference; CV: coefficient of variation; S*:significant at 5% probability level; NS: Non-significant; S**: significant at 1% probability level; S***: significant at 0.1% probability level; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence; m^2: square meters

Table 9. Grain yield, harvest index, shelling percentage, and sterility percentage as influenced by different weed management practices of spring maize at Dang, Nepal in 2023

Weed Management Practices	Grain yield (t ha^{-1})	Biological yield (t ha^{-1})	Harvest index	Shelling percentage	Sterility percentage
Weed free	6.14^{a}	15.18^{a}	40.42	80.77	14.27^{c}
Manual weeding	4.05^{bc}	11.14^{c}	36.98	77.73	18.18^{ab}
AtPrE	4.50^{b}	12.11^{bc}	37.14	78.56	17.10^{abc}
AtPoE	4.27^{bc}	11.4^{c}	37.62	78.12	17.88^{abc}
LaPoE	5.12^{ab}	13.32^{b}	38.34	79.14	16.52^{bc}
Mini tiller	3.89^{bc}	10.82^{cd}	35.47	77.99	18.33^{ab}
Weedy Check	2.96^{c}	9.13^{d}	32.95	77.55	20.69^{a}
F-test (α=0.05)	S**	S***	NS	NS	S*
SEM (±)	0.42	0.59	3.22	1.30	1.09
LSD (α=0.05)	1.29	1.83	9.92	4.02	3.37
CV (%)	16.52	8.66	15.08	2.87	10.79

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; NS: non-significant; SEM: standard error of the mean; LSD: Least significant difference; CV: coefficient of variation; S*:significant at 5% probability level; NS: Non-significant; S**: significant at 1% probability level; S***: significant at 0.1% probability level; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence; t ha^{-1}: tons per hectare

Table 10. Economic analysis of the treatments

Weed Management Practices	Total Cost of Cultivation (NPR ha^{-1})	Gross Return (NPR ha^{-1})	Net Return (NPR ha^{-1})	Benefit to Cost Ratio (B: C)
Weed free	174855	316633.30^{a}	141778.33^{ab}	1.81^{cd}
Manual weeding	103665	212833.30^{bc}	109168.33^{abc}	2.06^{bcd}
AtPrE	94530	235933.30^{b}	141403.33^{ab}	2.50^{ab}
AtPoE	94530	223183.30^{b}	128653.33^{ab}	2.36^{abc}
LaPoE	97995	266783.30^{ab}	168788.33^{a}	2.72^{a}
Mini tiller	100515	205083.30^{bc}	104568.33^{bc}	2.04^{bcd}
Weedy Check	92955	159183.30^{c}	66228.33^{c}	1.71^{d}
F-test (α=0.05)	-	S**	S*	S*
SEM (±)	-	18478.03	18478.03	0.19
LSD (α=0.05)	-	56936.49	56936.49	0.58
CV (%)	-	13.83	26.03	15.05

Note: Means followed by the same letter(s) in a column are not significantly different by DMRT at 5% level of significance; SEM: standard error of mean; LSD: Least significant difference; CV: coefficient of variation; S*: significant at 5% probability level; S**: significant at 1% probability level; S***: significant at 0.1% probability level; AtPrE; Atrazine as pre-emergence; AtPoE: Atrazine as post-emergence; LaPoE: Tembotrione as post-emergence; NPR ha^{-1}: Nepalese rupee per hectare; price of maize grain: NPR 45/kg

Discussion

Morphological and Phenological Traits

This study examines the effect of different weed control methods on the morphological and phenological traits of maize plants. There was no evidence of a statistically significant effect of weed control methods on plant height. Nonetheless, weed-free plots and LaPoE plots consistently resulted in higher plant heights at all stages of observation. Studies conducted by Safdar et al. (2011) and Shrestha et al. (2021) also reported no significant effect of weed control methods on plant height. The use of the same variety might be an explanation for this result. Plant height is primarily influenced by genotype rather than its environment; agronomic practices, such as weed control methods alone, do not impose a significant effect (Safdar et al., 2011). However, Alptekin et al. (2023) and Ikhajiagbe et al. (2023) reported a significant effect of weed management practices on the height of maize plants. These varying outcomes underscore the intricate relationship between weed control methods and plant height, which can vary based on specific plant genotypes, environmental conditions, and weed control strategies.

Similarly, there was no significant effect of weed control methods on the days to tasseling and silking. Nonetheless, there was a pronounced trend toward fewer days to tasseling and silking with weed-free plots and Tembotrione plots. Our results align with the studies conducted by Acharya et al. (2022) and Bhutto (2019) who reported no significant effect of weed control methods on the days to tasseling and silking. While individual weed control methods did not exert a statistically significant impact on plant height or phenological traits, the sustained effectiveness observed in both the weed-free and Tembotrione treatments, resulting in enhanced plant height and accelerated phenological growth, underscores the efficacy of weed-free environments.

Weed Parameters

This study examines the effect of weed control methods on weed dynamics and their efficiency in controlling weed populations in the field. It is crucial to control weed populations to maximize maize yields because weeds compete vigorously for essential resources like light, water, and nutrients. Weed control methods significantly affected both weed density and weed dry weight. The weed-free plot consistently showed lower weed density and dry weight at all observation stages compared to the higher values seen in the weedy check. After the weed-free plot, AtPrE resulted in lower values at 30 DAS, while LaPoE exhibited lower values at 45 and 60 DAS. This result aligns with the findings of Arivukkarasu et al. (2020) and Sharma et al. (2018) who documented the lowest weed density and total dry weight with the combined application of tembotrione and atrazine. Kaur et al. (2019) also reported the lowest total weed density and weed biomass in weed-free plots, followed by the application of tembotrione at 120 g/ha along with surfactant relative to other control methods, including atrazine.

The study also found that weed control methods had a significant impact on weed control efficiency, weed control index, and weed index. Weed-free plots consistently demonstrated the highest levels of weed control efficiency and weed control index, whereas weedy check plots exhibited the lowest values. After the weed-free plot, LaPoE exhibited higher efficiency in controlling the weed, which was statistically similar to AtPrE at 60 DAS. This result aligns with the findings of Arivukkarasu et al. (2020) and Sharma et al. (2018) who reported higher weed control efficiency and weed control index with the combined application of tembotrione and atrazine. Kaur et al. (2019) also reported the lowest weed index in the application of tembotrione at 120 g/ha along with surfactant. Frequent removal of weeds under weed-free plots is the most probable reason for its superiority in weed management. LaPoE's superior effectiveness in controlling weed after weed-free plot can be attributed to its post-emergence application, allowing for targeted and timely weed control (Kaur et al., 2019, Sharma et al., 2023). LaPoE also combines two herbicides, tembotrione and atrazine, with different modes of action, which leads to better weed control because of the synergistic effect achieved by targeting multiple biochemical pathways in the weed (Bagale, 2023). In summary, tembotrione showed higher efficiency in weed control and management after weed-free plot which can be attributed to its post-emergence application and its dual herbicide composition targeting multiple biochemical pathways in weeds.

Yield and Yield Parameters

Weeds significantly impact yield-attributing parameters in maize plants by competing for essential resources like light, water, and nutrients, leading to reduced growth and yield (Alptekin et al., 2023). Effective weed management practices are crucial for reducing weed competition, minimizing detrimental effects, and optimizing resource utilization by maize plants, ultimately leading to increased crop yield and productivity. The study found a statistically significant impact of weed control methods on cob length, number of kernels per row, and thousand-grain weight, with no significant variation observed in cob girth, number of rows per cob, and cob harvested per m^2.

Compared to other treatments, weed-free plots, and those treated with LaPoE showed superior cob length, number of kernels per row, and thousand-grain weight. Previous studies by Kaur et al. (2019), Sharma et al. (2018) and Shrestha et al. (2018) also reported increased cob length and thousand-grain weight in response to weed-free plots followed by the application of tembotrione and atrazine, aligning with our findings. Rana et al. (2018) observed that various weed control methods significantly impact the number of kernels per row, with the highest kernel count per row recorded in plots treated with tembotrione combined with a surfactant at a dosage of 150 g/ha. The improved yield-attributing characteristics in weed-free plots and LaPoE-treated plots can be attributed to the higher efficiency of weed management practices in these treatments. This is supported by the lower weed density, reduced dry weight, and higher weed control index and efficiency observed under these treatments, which minimized weed-crop competition and enhanced nutrient utilization by maize plants. Improvements in certain yield attributing parameters, including cob length, number of kernels per row, and thousand-grain weight, were observed because of this effect. This aligns with the findings of Alptekin et al. (2023), Ramesha et al. (2019) and Sarma & Gautam (2006) who reported better yield attributing parameters in those treatments that efficiently limited weed growth.

Weed control methods significantly influenced the yield parameters of maize, except for the harvest index (Table 9). The weed-free plot resulted in the highest grain yield and biological yield, which was statistically similar to LaPoE. Conversely, weedy check resulted in minimum grain yield and biological yield, which were statistically at par with mini tiller treatment. Studies conducted by Kaur et al. (2019), Rana et al. (2018), Sharma et al. (2023) and Sharma et al. (2018) reported higher grain yields under the application of tembotrione and atrazine, which is consistent with our finding. Arivukkarasu et al. (2020) also observed higher biological yield in response to tembotrione and atrazine and a minimum under the weedy check. Improved grain yield and biological yield in response to weed-free and LaPoE can be attributed to limited weed growth and improved yield attributing parameters under them. Studies by Alptekin et al. (2023), D et al. (2001), and Safdar et al. (2011) demonstrated a negative correlation between grain yield and dry biomass accumulation of weed. Similarly, Tahir et al. (2009) reported that all weed control methods led to an increase in grain yield compared to the weedy check, with improvements ranging from 29% to 78%, attributed to a higher number of grains per cob and a greater thousand-grain weight compared to the weedy check. These are in line with our findings that showed higher grain yield under weed-free and LaPoE that exhibited significantly lower weed dry weight and higher number of kernels per row and thousand-grain weight. Likewise, diminished grain yield and biological yield observed in the weedy check treatment can be ascribed to intense competition for vital resources such as nutrients, water, and space encountered by maize plants from weeds throughout their growth cycle, including critical stages.

In conclusion, effective weed management practices, as demonstrated by weed-free plots and LaPoE treatment, not only minimize weed competition but also optimize resource utilization by maize plants, leading to improved yield attributing parameters and ultimately higher crop yield and productivity.

Economic Analysis

LaPoE resulted in the highest net return and benefit-cost ratio, which was statistically on par with the application of AtPrE. Shrestha et al. (2018) also reported the highest net return and benefit-cost ratio in tembotrione and atrazine-treated plots. Weed free plot had the highest gross return but a lower net return and benefit: cost ratio. This can be attributed to the higher cost of cultivation associated with routine weed clearance. Weedy check had the lowest cost of production but the lowest returns and benefit-cost ratio because of the yield reduction caused by weed competition. In line with this, AtPrE treatment in our study emerged as the next best option in terms of returns and benefit-to-cost ratio. Shrestha et al. (2021) also reported similar findings, in which atrazine as PE was stated as the second-best alternative for the control of weeds.

Conclusion

In conclusion, this study underscores the significance of weed control methods in shaping various aspects of maize cultivation, from morphological and phenological traits to yield parameters and economic viability. Fifteen different weed species belonging to seven different families were observed in the experimental field. Major weed species identified in the field include *Cyperus rotundus, Cyperus esculentus, and Argemone Mexicana*. Weed-free plots and LaPoE stood out and showed superior performance in terms of both better weed management and higher yield, highlighting the importance of effective weed management strategies in maximizing maize production. Similarly, the results of economic analysis highlight the importance of considering both yield outcomes and the cost-effectiveness of weed control methods. LaPoE treatment resulted in superior economic returns, highlighting the economic viability of this strategy.

Limitations of the Study

Though this study provides detailed insights regarding the effects of different weed management techniques on spring maize at Dang, Nepal, it has some limitations. Our study was conducted in a single location in a single season due to which its applicability and generalization are somehow narrowed. That’s why future research must be performed in multiple locations within multiple seasons to finally achieve the insights of the study on a large scale.

Despite the fact this study is focused on the economics of production for each treatment so that an economical treatment can be recommended to the farmers, the variation in the price of grain as well as the herbicides applied, has imposed some limitations in the study.

Recommendations

Thus, our study suggests that farmers can effectively manage weeds, increase their crop productivity, and achieve a higher economic return with the application of tembotrione 42% (SC + surfactant) plus Atrazine 50% WP i.e. LaPoE. Future research in maize weed management could explore alternative methods, such as integrated pest management or biological control agents to minimize environmental impact while maintaining crop productivity. Long-term studies on the sustainability of weed control methods, including their effects on soil health and weed seedbanks, could provide valuable insights for developing more sustainable weed management practices. Furthermore, mechanistic studies exploring the molecular and physiological interactions between weeds and maize plants could offer valuable insights for the development of targeted weed management strategies. Overall, continued exploration in these areas could advance weed management practices and significantly contribute to the development of more sustainable maize production systems.

Declarations

Author Contribution Statement

Manjul Devkota: Performed and designed the experiments experimental setup, data collection, analyzed and interpreted the data, literature review, wrote the paper, proofreading, and revision.

Rijwan Sai: Data collection, analyzed and interpreted the data, methodology design, literature review, wrote the paper, proofreading and revision.

Aavash Shrestha: Data analysis, softwares, results and discussion, proofreading and review

Shiva Chaudhary: Data collection, proofreading, review, revision, wrote the paper

Prajjwal Koirala: Data interpretation, generated figures, software, proofreading and review

Mohan Mahato: Supervision, conceptualization, methodology, review and proofreading

Fund statement

This research didn't receive any specific funding

Conflict of Interest

The authors declare no conflict of interest

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