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RESEARCH ARTICLE

A comparative analysis of hand weeding and herbicides application on weed control, nutrient balance, yield and economics of maize (*Zea mays* L.)

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Abstract

Weeds impose significant challenges in maize production, leading to decreased grain yield and profit. The crop-weed competition for plant's required resources like light, water and nutrients, ultimately hinders maize growth and yield. To address this concern, field experiments were conducted for two years (*Kharif* 2021 and 2022) at the Experimental Farm, Annamalai University, Annamalai Nagar, India and compared the effects of hand weeding with those of sequential and sole application of Pre-Emergence (PE) and Post-Emergence (PoE) herbicides in maize. The experiment was designed under a randomized complete block design with three replications and nine treatments. The treatments consisted of unweeded control (T_1), hand weeding twice at 15 and 30 Days After Sowing (DAS) (T_2), PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS (T_3), PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS (T_4), PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_5), PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS (T_6), PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS (T_7), PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_8) and PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS (T_9). The results indicated that hand weeding twice at 15 and 25 DAS recorded significantly superior weed control efficiency (89.82 and 83.31 %), weed control index (90.11 and 87.87 %), maize growth attributes and grain yield (6732 and 6831 kg ha^{-1}) and stover yield (10920 and 11071 kg ha^{-1}) during the years 2021 and 2022 respectively. However, it was on par with PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1}/ tembotrione at 120 g a.i ha^{-1} on 18 DAS. This suppressed the weeds nutrient uptake and enhanced nutrient uptake by maize. Thus, lower post-harvest actual balance and net gain of soil available nutrients were noticed with these treatments. Concerning economics, PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS may offer a more effective way to increase profitability in maize cultivation.

Keywords: atrazine; nutrient uptake; tembotrione; topramezone; weed indices

Abbreviations: CGR-Crop Growth Rate; DAS-Days After Sowing; LAI-Leaf Area Index; PE-Pre-Emergence; PoE-Post-Emergence; WCE-Weed Control Efficiency; WCI-Weed Control Index

Introduction

Maize (*Zea mays* L.), the third most important food grain crop, it plays a vital role in both the agricultural economy and global food security. Maize is often referred to as the "queen of cereals" owing to its higher genetic potential which thrives well in diverse soil and climatic conditions in over 170 countries. Maize plays a vital role in human food (25 %), animal feed (12 %), poultry feed (49 %), starch (12 %), brewery (1 %) and seed (1 %) industries. In 2023-24, globally maize was cultivated in an area of 200.45 million hectares with the production of 1157 million tonnes and the productivity of 5.78 t ha^{-1}. Whereas in India, it was cultivated in an area of 10.74 million hectare with production of 38.09 million tonnes and productivity of 3.54 t ha^{-1}(1). Globally, India ranks fourth in area under maize cultivation and seventh in production, contributing to 4 % of the world's maize area and 2 % of global production. Being the day-neutral C_4 crop, maize is cultivated in all the major seasons of India.

Notably, over 80 % of maize is cultivated during the *Kharif* season especially under rainfed conditions, making the crop vulnerable to a variety of biotic stresses such as weeds, pests and diseases, as well as abiotic stresses like drought, heat and waterlogging (2,3).

The inadequate weed management practices during the critical period of crop-weed competition can cause a yield loss of 28-100 % in maize (4,5). Despite its higher monetary returns, the reduction in maize grain yield below the genetic potential highlights the need for better weed management practices to achieve the potential yield. Factors such as wider row spacing, slow initial growth and high fertilizer application in maize favour weed growth, leading to a reduction in grain yield. Herbicides remain a key tool in effective weed management, offering timely and efficient weed control at a lower cost compared to manual weeding. It is essential to employ a combination/sequential application of herbicides with different modes of action to reduce the risk of weed resistance and alteration in herbicide efficacy (6,7). The applications of both PE and PoE herbicides at appropriate times can help to manage the weeds throughout the crop weed competition period in maize. For instance, sequential application of atrazine at 1 kg a.i. ha^{-1} (PE) followed by tembotrione at 125 g a.i. ha^{-1} (PoE) resulted in the lowest weed dry biomass and the highest growth parameters and yield in maize (8). Similarly, the application of atrazine at 0.5 kg a.i. ha^{-1} (PE) followed by topramezone at 25.2 g a.i. ha^{-1} (PoE) significantly reduced the weed density and improved the grain yield in maize (9). The early post-emergence application of tembotrione at 80-100 g/ha + atrazine at 500 g/ha recorded the lowest weed density, weed dry weight and weed index; and the highest weed control efficiency, growth and yield (10). Thus, the use of PE herbicides, particularly atrazine, along with PoE herbicides such as topramezone, tembotrione and halosulfuron methyl, plays a crucial role in controlling weeds during both the early and later stages of weed emergence.

In addition, the weeds competition for nutrient uptake reduces the nutrient uptake by maize; thereby, it reduces the soil available nutrients and balance after the harvest of maize. For example, the higher nutrient uptake by weeds reduced the maize nutrient uptake, viz., nitrogen (by 33.03 %), phosphorus (33.33 %) and potassium (21.21 %) in weedy check as compared to the weed-free plants, which further reduced the actual balance, apparent gain and net gain of soil nutrients (11). However, the studies on the effect of new-generation herbicides on soil nutrient balance after the harvest of maize is limited. Hence, we hypothesized that the sequential application of pre- and PoE herbicides could reduce the crop-weed competition and increase the crop nutrient uptake, yield and soil nutrient balance in maize. Considering these facts, field experiments were conducted over two consecutive *Kharif* seasons (2021 and 2022) with the objectives of comparing the effect of weed management practices viz., hand weeding and herbicide application on (i) weed control and maize growth, (ii) yield and economics of maize and (iii) nutrient uptake and soil nutrient balance after harvest of maize.

Materials and Methods

Experimental site details

Two years of field experiments were conducted during *Kharif* (June to September) 2021 and 2022 at B. Mutlur, Chidambaram, Tamil Nadu, India. The experimental site is located at 11.46° N and 79.70° E at an altitude of 5.8 m above mean sea level in the agro-climatic zone of east coast plains and hills region (zone 11). The weekly mean maximum temperature during the cropping season (*Kharif*) in 2021 and 2022 ranged from 38.6 °C to 32.6 °C and 37.8 °C to 32.3 °C, respectively (Fig. 1a, b). Whereas, the weekly mean minimum temperature ranged from 26.2 °C to 23.1 °C in 2021 and from 25.2 °C to 23.6 °C in 2022. Similarly, the relative humidity ranged from 79 % to 90 % and 64 % to 81 % with bright sunshine ranging from 2.8 to 8.2 hr and 3.3 to 7.5 hr during *Kharif* 2021 and 2022 respectively. Total rainfall of 385.4 mm and 269.1 mm was recorded during the cropping season in 2021 and 2022 respectively. The experimental site consisted of clayey loam soil with low available nitrogen (225.45 kg ha^{-1}), medium available phosphorus (18.20 kg ha^{-1}) and high available potassium (322.80 kg ha^{-1}).

Experimental design and field management

The field experiments were conducted in a randomized complete block design with three replications. The treatments consisted of unweeded control (T_1), hand weeding twice at 15 and 30 DAS (T_2), PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS (T_3), PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS (T_4), PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_5), PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS (T_6), PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS (T_7), PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_8) and PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS (T_9). The stubbles of the previous season's rice crops and weeds were removed from the experimental area and the soil was prepared to a fine tilth. The maize hybrid Ankur Aditya (Ankur Seeds Pvt. Ltd., New Delhi) was sown on June 8th and June 5th in 2021 and 2022, respectively. The recommended quantity of nutrients, i.e., 250:75:75 kg $N:P_2O_5:K_2O$ per hectare, was supplied using urea, single super phosphate and muriate of potash, respectively. Half (50 %) the quantity of nitrogen (N) and 100 % of phosphorus (P) and potassium (K) were applied as basal at sowing. The remaining 50 % of nitrogen was top-dressed at the knee-height stage of maize. Irrigation was scheduled based on 50 % depletion of available soil moisture as per field capacity. As per the treatment requirements, the required quantity of formulated product of herbicides was diluted in 500 L of water ha^{-1} and sprayed as PE (3 DAS) / PoE herbicides (18 DAS) using a knapsack sprayer equipped with a flood jet nozzle.

Plant growth parameters

The growth parameters of maize viz., plant height and dry matter production were recorded at 30 DAS, 60 DAS and at harvest stages. The above-ground plant parts were collected, shade-dried for two days and dried in a hot air oven at 65 °C until a steady weight was obtained and the dry matter production was recorded. Whereas, the Leaf Area Index (LAI) was recorded at flowering stage (Eqn. 1) (12).

$$LAI = \frac{\text{Leaf area}}{\text{Ground area}} \qquad \text{(Eqn. 1)}$$

Similarly, the Crop Growth Rate (CGR) between 0-30 DAS, 30-60 DAS and 60 DAS-Harvest stage was calculated with the formula and expressed as g m^{-2} day^{-1} (Eqn. 2) (12).

$$CGR = \frac{W_2 - W_1}{(t_2 - t_1)S} \qquad \text{(Eqn. 2)}$$

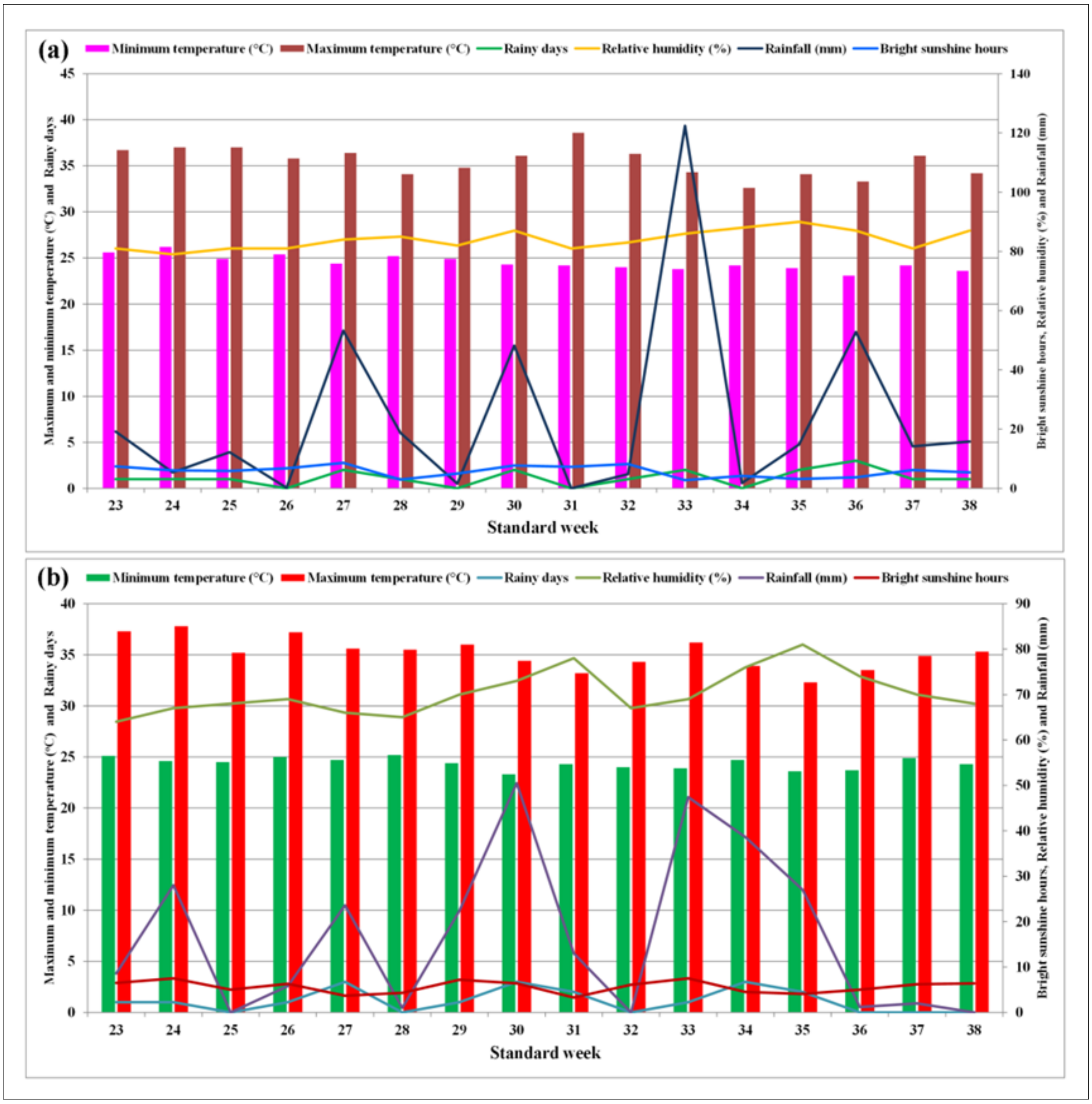

Fig. 1. Weather parameters of standard meteorological weeks observed during experimental periods. (a) *Kharif* 2021; (b) *Kharif* 2022

Where,

W_1 - Dry weight of plant at time t_1

W_2 - Dry weight of plant at time t_2

S - Land area in cm^2

Weed growth and indices

Total weed density

The total weed density at 30 and 45 DAS was counted in each plot from four randomly selected areas (0.25 m^2) using 0.5 m × 0.5 m quadrate, the mean was calculated and expressed as number per m^2.

Weed dry weight

Weeds from the selected four quadrants were collected at 30 and 45 DAS and shade-dried for two days. Later the samples were dried in a hot air oven at 65 °C till a constant weight was obtained and expressed in g m^{-2}.

Weed Control Efficiency (WCE)

WCE of each treatment was determined with the following formula and expressed as a percentage (Eqn. 3) (13).

$$\text{WCE}(\%) = \frac{\text{Weed population in control plot - Weed population in treated plot}}{\text{Weed population in control plot}} \times 100 \quad \text{(Eqn. 3)}$$

Weed Control Index (WCI)

WCI of each treatment was calculated by using the formula as suggested in a previous study and is expressed as percentage (Eqn. 4) (14).

$$\text{WCI}(\%) = \frac{\text{Weed dry weight in control plot - Weed dry weight in treated plot}}{\text{Weed dry weight in control plot}} \times 100 \quad \text{(Eqn. 4)}$$

Yield attributes, yield and economics

The yield attributes of maize viz., number of grains per cob and 100 grain weight and yields viz., grain and stover yields were recorded at the harvest stage. Similarly, the net returns, gross returns and benefit-cost ratio were calculated based on the cost of cultivation and income obtained from maize grain and stover.

Nutrient uptake by weed and crop

The hot air oven-dried maize plant samples at the harvest stage were crushed, powdered and digested with acids for analysing nutrient content viz., total nitrogen (N) by micro-Kjeldahl technique (15), phosphorus (P) by calorimetric technique and potassium (K) using flame photometer (16). Similarly, the collected weed samples at 30, 60 and 90 DAS were oven-dried, digested with the reaction mixtures and analysed the nutrient content. Subsequently, the total nutrient uptake viz., N, P and K by weeds and maize were calculated with the following formula (Eqn. 5) (17).

$$\text{Nutrient uptake (kg ha}^{-1}) = \frac{\text{Nutrient content in sample (\%)} \times \text{Total dry matter production(kg ha}^{-1})}{100} \qquad \text{(Eqn. 5)}$$

Soil nutrient analysis

After harvesting the crop, soil samples were thoroughly mixed into composite samples to ensure representation. These bulk soil samples were dried, ground and sieved through a 2 mm mesh for further analysis of soil nutrients. Available nitrogen (N) was determined using the alkaline potassium permanganate method, whereas available phosphorus was determined using the ascorbic acid blue method with a calorimeter and available potassium was assessed using the neutral normal ammonium acetate method with a flame photometer (16,18,19).

Nutrient balance sheet

The nutrient balance after the harvest of maize was derived from the difference between the total quantity of nutrients applied and the total quantity of specific nutrients removed by weeds and maize. The balance of individual nutrients was calculated by the difference between soil nutrient status at the harvest stage and soil nutrient status at the initial stage as per the procedure suggested in a previous study (Eqn. 6-8) (20) and expressed in kg ha^{-1} (either positive or negative).

Expected balance (E)

= Initial nutrient status (A) + Nutrient added (B) - Nutrient uptake by weeds (C) - Nutrient uptake by crop (D) (Eqn. 6)

Apparent gain (G)

= Actual balance (F) - Expected balance (E) (Eqn. 7)

Net gain (H)

= Actual balance (F) - Initial nutrient status (A) (Eqn. 8)

Statistical analysis

The data collected on maize growth, weed control indices, yield, nutrient uptake and soil nutrient balance were subjected to a normality test before performing analysis of variance. The mean values of total weed density and weed dry weight were normalized by square root transformation ($\sqrt{x} + 0.5$). Further, Analysis of Variance (ANOVA) was conducted separately for two years under a randomized complete block design with three replications. The weed management practices were considered as fixed effects and replications as random effects. The significant difference was tested using Duncan's Multiple Range Test (DMRT) test ($\alpha = 0.05$) using GrapesAgri1 Version 1.1.0 (21).

Results and Discussion

Maize is a staple food crop for around 200 million people globally (22). The demand for maize is projected to double by 2050 in developing countries. However, maize productivity in India (3.01 kg ha^{-1}) is nearly half of the global average (5.82 kg ha^{-1}) (23). To achieve higher maize productivity, it is crucial to enhance crop management practices, particularly with efficient weed management strategies. In this line, an attempt was made to compare the hand weeding with different herbicides in maize and the results are discussed here.

Weed indices and maize growth

The different weed management practices had a significant effect ($p < 0.05$) on the growth of weed and maize and weed indices during both the years (Table 1, 2). The removal of weeds between and within rows through hand weeding twice at 15 and 30 DAS (T_2) recorded significantly the highest WCE (89.82 and 83.31 %) and WCI (90.11 and 87.87 %) due to the reduction in total weed density and weed dry weight (Table 1). The improved soil physical condition and aeration caused by hand weeding had enhanced maize access to space, water and light which might have improved the root proliferation (24). This optimal condition for growth and development increased CGR during the early (from 0 to 30 DAS by 104.62 % and 91.98 %) and mid-vegetative (from 30 to 60 DAS by 97.71 % and 99.27 %) growth stages during 2021 and 2022 respectively (Table 2). Besides, the increased uptake of N (by 64.67 % and 65.42 %), P (69.94 % and 69.91 %) and K (103.92 % and 104.44 %) over unweeded control (T_1) had amplified the plant height and LAI ultimately resulting in the highest dry matter production (Table 2–5). However, it was on par with the PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS (T_7) and PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_8). Atrazine blocks the electron transport chain in chloroplasts and affects photosynthesis in weeds (25,26). This suppressed the weed density and created a weed-free environment, preventing crop-weed competition during the early stages of growth and ensured higher nutrient availability to maize (27).

Further, the sequential application of novel herbicides viz., topramezone at 25.2 g a.i ha^{-1} or tembotrione at 120 g a.i ha^{-1} on 18 DAS reduced the total weed density (by 87.83-88.80 % and 82.55-83.32 %) and weed dry weight (by 88.19-89.11 % and 84.64-86.57 %) which decreased the crop weed competition and improved the maize growth as compared to the treatments with one-time herbicide application (T_3, T_4, T_5 and T_6). Similarly, recent studies have shown the excellence of tembotrione in controlling broadleaf and grassy weeds in maize (28,29). For instance, the application of topramezone at 100 g L^{-1} caused strong photobleaching effects on shoots of weeds due to the inhibition of 4-hydroxyphenylpyruvate dioxygenase within 2-5 days of treatment (30). Conversely, the highest total weed density and weed dry weight and the lowest plant height, dry matter production, LAI and CGR were registered with the unweeded control (T_1). In brief, the sequential application of pre (atrazine at 1 kg a.i ha^{-1} on 3 DAS) and post (topramezone at 25.2 g a.i ha^{-1} or tembotrione at 120 g a.i ha^{-1} on 18 DAS) emergence herbicides (T_7/T_8) suppressed the weed growth and improved maize growth which was statistically on par with hand weeding twice at 15 and 30 DAS (T_2).

Table 1. Effect of weed management practices on weed growth and indices

Treatment	Total weed density (no. m^{-2})				Weed dry weight (g m^{-2})				Weed control efficiency (%)				Weed control index (%)			
	30 DAS		45 DAS		30 DAS		45 DAS		30 DAS		45 DAS		30 DAS		45 DAS	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1*	16.10^{a†} (259.29)	16.38^{a} (268.24)	19.41^{a} (376.52)	19.73^{a} (389.25)	13.97^{a} (195.21)	14.22^{a} (202.21)	16.89^{a} (285.21)	17.16^{a} (294.25)	-	-	-	-	-	-	-	-
T_2	3.49^{i} (12.12)	4.28^{h} (14.26)	6.20^{i} (38.34)	6.95^{g} (48.29)	2.98^{i} (8.85)	3.65^{h} (13.25)	5.32^{i} (28.21)	5.98^{h} (35.69)	95.33^{a}	93.19^{a}	89.82^{a}	83.32^{a}	95.47^{a}	93.91^{a}	90.11^{a}	87.87^{a}
T_3	10.10^{b} (101.91)	10.52^{b} (110.56)	14.73^{b} (216.83)	15.11^{b} (228.19)	8.73^{b} (76.21)	9.03^{b} (81.42)	12.74^{b} (162.32)	13.34^{b} (175.24)	60.70^{e}	58.78^{e}	42.41^{e}	21.11^{f}	60.96^{e}	60.03^{e}	43.09^{e}	40.45^{f}
T_4	6.86^{e} (46.95)	7.45^{e} (56.85)	10.76^{e} (115.82)	11.38^{e} (129.41)	5.91^{e} (34.85)	6.37^{e} (40.54)	9.29^{d} (86.25)	9.76^{d} (95.21)	81.89^{c}	78.81^{c}	69.24^{c}	55.26^{c}	82.15^{c}	80.35^{c}	69.76^{c}	67.64^{d}
T_5	7.15^{d} (51.06)	8.00^{d} (63.89)	11.06^{d} (122.37)	11.76^{d} (138.14)	6.16^{d} (37.85)	6.58^{d} (43.29)	9.55^{d} (91.21)	9.92^{d} (98.36)	80.31^{c}	76.18^{c}	67.50^{c}	52.24^{d}	80.61^{c}	78.98^{c}	68.02^{c}	66.57^{d}
T_6	8.56^{c} (73.24)	9.46^{c} (89.52)	12.79^{c} (163.58)	13.36^{c} (178.36)	7.37^{c} (54.21)	7.71^{c} (59.43)	11.01^{c} (121.25)	11.44^{c} (130.78)	71.75^{d}	66.63^{d}	56.55^{d}	38.34^{e}	72.23^{d}	70.96^{d}	57.49^{d}	55.55^{e}
T_7	3.73^{h} (13.83)	3.91^{h} (15.25)	6.50^{f} (42.18)	6.95^{g} (48.25)	3.18^{h} (10.05)	3.64^{h} (13.21)	5.58^{h} (31.06)	6.29^{g} (39.52)	94.67^{a}	94.31^{a}	88.80^{a}	83.30^{a}	94.85^{a}	93.93^{a}	89.11^{a}	86.57^{ab}
T_8	3.96^{g} (15.64)	4.69^{g} (21.96)	6.77^{g} (45.84)	7.11^{g} (50.48)	3.39^{g} (11.45)	3.91^{g} (15.25)	5.81^{g} (33.69)	6.73^{f} (45.21)	93.97^{a}	91.81^{a}	87.83^{a}	82.55^{a}	94.13^{a}	92.92^{ab}	88.19^{a}	84.64^{b}
T_9	5.27^{f} (27.75)	5.93^{f} (35.14)	8.72^{f} (76.06)	9.24^{f} (85.24)	4.53^{f} (20.51)	4.55^{f} (20.69)	7.48^{f} (55.92)	7.78^{e} (60.45)	89.30^{b}	86.90^{b}	79.80^{b}	70.53^{b}	89.49^{b}	90.21^{b}	80.39^{b}	79.46^{c}
SE. m ±	0.06	0.06	0.08	0.08	0.05	0.05	0.07	0.07	1.15	1.13	1.04	0.99	1.04	1.14	1.05	1.02

Means followed by the same letter (s) within the column are not significantly differed ($p<0.05$). *T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 - PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS

Table 2. Effect of weed management practices on maize growth parameters

Treatment	Plant height (cm)						Dry matter production (g plant^{-1})						Leaf Area Index		Crop growth rate (g m^{-2} day^{-1})					
	30 DAS		60 DAS		At harvest		30 DAS		60 DAS		At harvest		Flowering stage		0-30 DAS		30 - 60 DAS		60 DAS - Harvest	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1*	36.54^{f†}	39.58^{g}	78.56^{f}	85.26^{g}	111.21^{f}	120.56^{g}	13.25^{g}	14.38^{i}	47.82^{f}	49.01^{f}	98.21^{f}	99.57^{f}	3.15^{f}	3.29^{f}	3.68^{g}	3.99^{f}	9.60^{f}	9.62^{f}	7.00^{f}	7.02^{f}
T_2	81.27^{a}	85.98^{a}	181.25^{a}	198.24^{a}	227.39^{a}	240.24^{a}	27.11^{a}	27.59^{a}	95.42^{a}	96.60^{a}	169.08^{a}	171.86^{a}	5.45^{a}	5.56^{a}	7.53^{a}	7.66^{a}	18.98^{a}	19.17^{a}	10.23^{a}	10.45^{a}
T_3	46.17^{e}	50.58^{f}	102.84^{e}	115.69^{f}	133.21^{e}	139.45^{f}	15.62^{f}	16.43^{h}	60.13^{e}	60.74^{e}	114.71^{e}	116.40^{e}	3.61^{e}	3.69^{e}	4.34^{f}	4.56^{e}	12.36^{e}	12.31^{e}	7.58^{e}	7.73^{e}
T_4	62.75^{c}	67.89^{c}	141.37^{c}	154.65^{c}	181.52^{c}	195.26^{c}	21.24^{d}	21.90^{e}	76.64^{c}	78.08^{c}	141.30^{c}	143.53^{c}	4.53^{c}	4.63^{c}	5.90^{d}	6.08^{c}	15.39^{c}	15.60^{c}	8.98^{c}	9.09^{c}
T_5	61.92^{c}	63.85^{d}	139.55^{c}	145.58^{d}	179.17^{c}	186.89^{d}	20.74^{d}	21.54^{f}	74.96^{c}	76.31^{c}	138.25^{c}	140.42^{c}	4.49^{c}	4.58^{c}	5.76^{d}	5.98^{c}	15.06^{c}	15.21^{c}	8.79^{c}	8.90^{c}
T_6	53.17^{d}	56.85^{e}	119.12^{d}	128.46^{e}	154.92^{d}	161.25^{e}	18.18^{e}	18.94^{g}	67.55^{d}	68.53^{d}	126.42^{d}	128.35^{d}	4.05^{d}	4.11^{d}	5.05^{e}	5.26^{d}	13.71^{d}	13.77^{d}	8.18^{d}	8.31^{d}
T_7	80.92^{a}	86.15^{a}	178.83^{a}	195.36^{a}	225.57^{a}	235.59^{a}	26.50^{ab}	27.30^{b}	94.45^{a}	95.57^{a}	166.76^{a}	169.50^{a}	5.41^{a}	5.49^{a}	7.36^{ab}	7.58^{a}	18.88^{a}	18.97^{a}	10.04^{a}	10.27^{a}
T_8	79.17^{a}	84.25^{a}	176.98^{a}	191.21^{a}	222.75^{a}	232.45^{a}	26.11^{b}	26.69^{c}	92.54^{a}	94.77^{a}	164.65^{a}	167.35^{a}	5.38^{a}	5.45^{a}	7.25^{b}	7.41^{a}	18.45^{a}	18.91^{a}	10.02^{a}	10.08^{a}
T_9	71.54^{b}	75.51^{b}	159.65^{b}	165.25^{b}	201.91^{b}	210.98^{b}	23.68^{c}	24.24^{d}	84.08^{b}	85.89^{b}	153.01^{b}	155.47^{b}	4.96^{b}	5.01^{b}	6.58^{c}	6.73^{b}	16.78^{b}	17.12^{b}	9.57^{b}	9.66^{b}
SE. m ±	0.94	1.00	2.09	2.27	2.63	2.75	0.31	0.06	1.11	1.12	1.98	2.02	0.06	0.06	0.08	0.09	0.22	0.22	1.22	1.24

Means followed by the same letter (s) within the column are not significantly differed ($p<0.05$). *T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 - PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS

Table 3. Effect of weed management practices on soil available nitrogen (kg ha^{-1}) balance after harvest of maize

Treatment	Initial status (A)		Added (B)		Uptake by weeds (C)		Uptake by crop (D)		Expected balance (E; E=A+B-C-D)		Actual balance (F)		Apparent gain (G; G=F-E)		Net gain (H; H=F-A)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1*	225.45	233.03	250	250	87.84^{a†}	90.99^{a}	132.42^{f}	136.94^{f}	255.19^{e}	255.10^{e}	284.63^{a}	279.94^{a}	29.44^{a}	24.84^{a}	59.18^{a}	46.91^{a}
T_2	225.45	233.03	250	250	3.98^{f}	5.96^{f}	218.06^{a}	226.53^{a}	253.41^{e}	250.54^{e}	214.15^{e}	208.87^{f}	-39.26^{c}	-41.67^{c}	-11.3^{f}	-24.17^{h}
T_3	225.45	233.03	250	250	34.29^{b}	36.64^{b}	152.36^{e}	163.90^{e}	288.80^{a}	282.50^{a}	252.59^{b}	246.54^{b}	-36.21^{b}	-35.96^{b}	27.14^{b}	13.51^{b}
T_4	225.45	233.03	250	250	15.68^{d}	18.24^{d}	184.49^{c}	196.45^{c}	275.28^{bc}	268.34^{cd}	225.64^{d}	222.13^{d}	-49.64^{f}	-46.22^{e}	0.19^{d}	-10.91^{e}
T_5	225.45	233.03	250	250	17.03^{d}	19.48^{d}	180.80^{c}	192.73^{c}	277.62^{a-c}	270.82^{bc}	223.85^{de}	219.37^{de}	-53.77^{g}	-51.45^{f}	-1.60^{e}	-13.66^{f}
T_6	225.45	233.03	250	250	24.39^{c}	26.74^{c}	166.51^{d}	175.15^{d}	284.55^{ab}	281.14^{ab}	240.74^{cd}	236.93^{c}	-43.81^{e}	-44.21^{de}	15.29^{c}	3.89^{c}
T_7	225.45	233.03	250	250	4.52^{f}	5.94^{f}	215.26^{a}	223.88^{a}	255.67^{e}	253.21^{e}	214.37^{e}	210.08^{ef}	-41.30^{cd}	-43.13^{cd}	-11.08^{f}	-22.95^{gh}
T_8	225.45	233.03	250	250	5.15^{f}	6.86^{f}	212.70^{a}	219.18^{a}	257.60^{de}	256.99^{de}	214.59^{e}	211.30^{ef}	-43.01^{de}	-45.69^{e}	-10.86^{f}	-21.73^{g}
T_9	225.45	233.03	250	250	9.23^{e}	9.31^{e}	198.64^{b}	205.91^{b}	267.58^{cd}	267.81^{cd}	226.73^{d}	225.20^{d}	-40.85^{c}	-42.61^{cd}	1.28^{d}	-7.84^{d}
SE. m ±					0.52	0.54	2.57	2.70	3.67	3.61	3.12	3.07	0.67	0.66	0.48	0.46

Means followed by the same letter (s) within the column are not significantly differed ($p<0.05$). *T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 - PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS

Table 4. Effect of weed management practices on soil available phosphorus (P_2O_5 kg ha^{-1}) balance after harvest of maize

Treatment	Initial status (A)		Added (B)		Uptake by weeds (C)		Uptake by crop (D)		Expected balance (E; E=A+B-C-D)		Actual balance (F)		Apparent gain (G; G=F-E)		Net gain (H; H=F-A)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1*	18.2	19.24	75	75	11.71^{a†}	12.13^{a}	20.46^{f}	20.94^{g}	61.03^{cd}	61.17^{bc}	20.95^{a}	21.98^{a}	-40.08^{a}	-39.20^{ab}	2.75^{a}	2.73^{a}
T_2	18.2	19.24	75	75	0.53^{f}	0.80^{f}	34.77^{a}	35.58^{a}	57.90^{e}	57.87^{d}	18.12^{e}	19.23^{e}	-39.78^{a}	-38.64^{a}	-0.08^{g}	-0.02^{g}
T_3	18.2	19.24	75	75	4.57^{b}	4.89^{b}	23.58^{e}	23.93^{f}	65.05^{a}	65.43^{a}	20.35^{ab}	21.68^{ab}	-44.70^{d}	-43.75^{d}	2.15^{b}	2.43^{b}
T_4	18.2	19.24	75	75	2.09^{d}	2.43^{d}	28.75^{c}	30.17^{c}	62.36^{bc}	61.64^{bc}	19.31^{cd}	20.76^{c}	-43.05^{cd}	-40.89^{bc}	1.11^{d}	1.51^{d}
T_5	18.2	19.24	75	75	2.27^{d}	2.60^{d}	28.33^{c}	28.75^{d}	62.60^{a-c}	62.90^{ab}	19.36^{cd}	20.33^{cd}	-43.24^{cd}	-42.57^{cd}	1.16^{d}	1.08^{e}
T_6	18.2	19.24	75	75	3.25^{c}	3.57^{c}	25.95^{d}	26.32^{e}	64.00^{ab}	64.36^{a}	19.87^{bc}	20.96^{bc}	-44.13^{d}	-43.40^{d}	1.67^{c}	1.72^{c}
T_7	18.2	19.24	75	75	0.60^{f}	0.79^{f}	34.19^{a}	35.13^{a}	58.41^{de}	58.32^{d}	18.19^{e}	19.10^{e}	-40.22^{a}	-39.22^{ab}	-0.01^{g}	-0.14^{h}
T_8	18.2	19.24	75	75	0.69^{f}	0.92^{f}	33.66^{a}	34.37^{a}	58.85^{de}	58.96^{cd}	18.27^{e}	19.84^{de}	-40.58^{ab}	-39.12^{ab}	0.07^{f}	0.59^{f}
T_9	18.2	19.24	75	75	1.23^{e}	1.24^{e}	31.16^{b}	31.64^{b}	60.81^{cd}	61.37^{bc}	18.78^{de}	19.79^{de}	-42.03^{bc}	-41.58^{c}	0.58^{e}	0.55^{f}
SE. m ±					0.07	0.07	0.40	0.41	0.83	0.81	0.26	0.27	0.57	0.56	0.03	0.03

Means followed by the same letter (s) within the column are not significantly differed ($p<0.05$). *T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 -PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS

Table 5. Effect of weed management practices on soil available potassium (K_2O kg ha^{-1}) balance after harvest of maize

Treatment	Initial status (A)		Added (B)		Uptake by weeds (C)		Uptake by crop (D)		Expected balance (E; E=A+B-C-D)		Actual balance (F)		Apparent gain (G; G=F-E)		Net gain (H; H=F-A)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1*	322.80	316.67	75	75	70.27^{a†}	72.80^{a}	76.73^{f}	78.15^{f}	250.79^{d-f}	240.73^{de}	321.85^{a}	312.19^{a}	71.06^{b}	71.47^{b}	-0.95^{a}	-4.47^{a}
T_2	322.80	316.67	75	75	3.18^{f}	4.77^{f}	156.47^{a}	159.77^{a}	238.14^{g}	227.13^{f}	313.26^{d}	303.86^{d}	75.12^{a}	76.73^{a}	-9.54^{f}	-12.81^{f}
T_3	322.80	316.67	75	75	27.43^{b}	29.31^{b}	95.3^{e}	96.73^{e}	275.06^{a}	265.63^{a}	320.06^{ab}	310.46^{ab}	45.00^{f}	44.83^{g}	-2.74^{b}	-6.21^{b}
T_4	322.80	316.67	75	75	12.54^{d}	14.59^{d}	125.21^{c}	129.03^{c}	260.04^{b-d}	248.04^{b-d}	316.93^{b-d}	307.42^{b-d}	56.89^{d}	59.38^{d}	-5.87^{d}	-9.25^{d}
T_5	322.80	316.67	75	75	13.62^{d}	15.58^{d}	121.78^{c}	123.58^{c}	262.39^{bc}	252.51^{bc}	317.01^{b-d}	307.50^{b-d}	54.62^{d}	54.99^{e}	-5.79^{d}	-9.17^{d}
T_6	322.80	316.67	75	75	19.51^{c}	21.39^{c}	108.47^{d}	113.00^{d}	269.81^{ab}	257.27^{ab}	318.52^{a-c}	308.96^{a-c}	48.71^{e}	51.69^{f}	-4.28^{c}	-7.70^{c}
T_7	322.80	316.67	75	75	3.62^{f}	4.76^{f}	153.86^{a}	156.30^{a}	240.32^{fg}	230.62^{ef}	313.42^{d}	304.02^{d}	73.10^{ab}	73.40^{b}	-9.38^{f}	-12.65^{f}
T_8	322.80	316.67	75	75	4.12^{f}	5.49^{f}	151.48^{a}	155.79^{a}	242.20^{e-g}	230.39^{ef}	313.56^{d}	304.15^{d}	71.36^{b}	73.77^{b}	-9.24^{f}	-12.52^{f}
T_9	322.80	316.67	75	75	7.38^{e}	7.45^{e}	138.39^{b}	141.51^{b}	252.03^{c-e}	242.71^{cd}	315.41^{cd}	305.95^{cd}	63.38^{c}	63.23^{c}	-7.39^{e}	-10.72^{e}
SE. m ±					0.42	0.43	1.80	1.84	3.47	3.34	0.45	0.47	0.83	0.83	0.11	0.14

Means followed by the same letter (s) within the column are not significantly differed (p<0.05). *T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 -PoE application of topramezone at 25.2 g a.i ha^{-1}on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1}on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1}on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1}on 18 DAS

Nutrient uptake, balance and gain after harvest

The nutrient uptake by crop and its balance after harvest depends on the crop management practices including effective weed control measures (31,32). In this study, nutrient uptake viz., nitrogen (N), phosphorus (P) and potassium (K) of maize and weeds differed significantly (p <0.05) with different weed management practices. Hand weeding twice at 15 and 30 DAS (T_2) recorded the highest nutrient uptake viz., N (218.06 and 226.53 kg ha^{-1}), P (34.77 and 35.58 kg ha^{-1}) and K (156.47 and 159.77 kg ha^{-1}) due to the lowest nutrient uptake namely N (3.98 and 5.96 kg ha^{-1}), P (0.53 and 0.80 kg ha^{-1}) and K (3.18 and 4.77 kg ha^{-1}) by weeds favoured by weed free condition (Table 3-5). The lowest actual balance in T2 was due to highest nutrient extraction by maize, which indicates effective nutrient use rather than depletion. This resulted in the lowest expected and actual balance of NPK (31). However, it was on par with the treatments containing sequential application of pre and PoE herbicides i.e. PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1}on 18 DAS (T_7) and PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_8). Though the expected balance was highest with PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS (T_3), the actual balance was highest with unweeded control (T_1) due to the suppression in nutrient uptake of maize owing to higher crop weed competition. This resulted in the highest net gain of N (59.18 and 46.91 kg ha^{-1}), P_2O_5 (2.75 and 2.73 kg ha^{-1}) and K_2O (-0.95 and -4.47 kg ha^{-1}) during 2021 and 2022 respectively.

Similarly, T_1 recorded the highest apparent gain of N (29.44 and 24.84 kg ha^{-1}) due to impaired N uptake by maize as a result of higher weed total density (Table 1) and nutrient uptake. Whereas, the highest apparent gain of P_2O_5 (-39.78 and 38.64 kg ha^{-1}) and K_2O (75.12 and 76.73 kg ha^{-1}) was registered with T_2. The reduction in total weed density with T_7 and T_8 decreased the nutrient uptake by weeds and increased the uptake by maize which reduced the net gain after harvest (11). Similarly, another study reported an increase in the uptake of N (by 67.82 %), P (71.24 %) and K (70.97 %) in sorghum due to the reduction in nutrient uptake by weeds (33). Whereas, the lowest nutrient uptake by maize was recorded with unweeded control (T_1) due to the highest uptake by weeds. In precise, the timely weed management effectively reduced the nutrient uptake by weeds and increased its uptake by maize which in turn lessened the apparent and net gain of nutrients after harvest.

Yield and economics of maize

The acceptance of technology by the farming community depends on the yield and economic profitability. The different weed management practices had considerably (p <0.05) influenced the yield attributes, yield and economics of maize (Table 6, Fig. 2a-d). Among the different weed management practices, hand weeding twice at 15 and 30 DAS (T_2) registered the highest grain (6732 and 6831 kg ha^{-1}) and stover (136808 and 145095 kg ha^{-1}) yields (Table 6). This was mainly due to the favourable weed-free condition (as evidenced by the lowest weed total density and weed dry matter production) that prevailed during the vegetative growth stage of maize. Thus, it improved the WCE (89.82 and 83.31 %) and WCI (90.11 and 87.87 %) in 2021 and 2022 respectively and enhanced the maize growth parameters and yield attributes contributing to the highest grain and stover yields (Table 1, 6). These findings are

Table 6. Effect of weed management practices on yield attributes, yield and economics of maize

Treatment	Number of grains cob^{-1}		100-grain weight (g)		Grain yield(kg ha^{-1})		Stover yield(kg ha^{-1})	
	2021	2022	2021	2022	2021	2022	2021	2022
T_1*	131.32^{g†}	134.25^{g}	34.02^{a}	34.06^{a}	2880^{f}	2933^{f}	5822^{f}	5919^{f}
T_2	275.38^{a}	285.10^{a}	34.16^{a}	34.18^{a}	6732^{a}	6831^{a}	10920^{a}	11071^{a}
T_3	172.47^{f}	178.85^{f}	34.21^{a}	34.25^{a}	4011^{e}	4071^{e}	6781^{e}	6889^{e}
T_4	209.06^{d}	215.36^{d}	34.03^{a}	34.17^{a}	5365^{e}	5443^{c}	8856^{c}	8997^{c}
T_5	205.98^{d}	215.75^{d}	34.13^{a}	34.19^{a}	5218^{c}	5295^{c}	8662^{c}	8818^{c}
T_6	188.42^{e}	198.45^{e}	34.18^{a}	34.19^{a}	4610^{d}	4675^{d}	7734^{d}	7867^{d}
T_7	271.64^{ab}	278.14^{ab}	34.16^{a}	34.20^{a}	6633^{a}	6738^{a}	10777^{a}	10955^{a}
T_8	264.88^{b}	272.85^{b}	34.12^{a}	34.18^{a}	6552^{a}	6652^{a}	10664^{a}	10844^{a}
T_9	241.11^{c}	252.14^{c}	34.08^{a}	34.16^{a}	5952^{b}	6043^{b}	9722^{b}	9867^{b}
SE. m ±	3.18	3.32	0.45	0.41	78.22	79.34	126.63	128.54

Means followed by the same letter (s) within the column are not significantly differed ($p<0.05$). *T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 - PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS

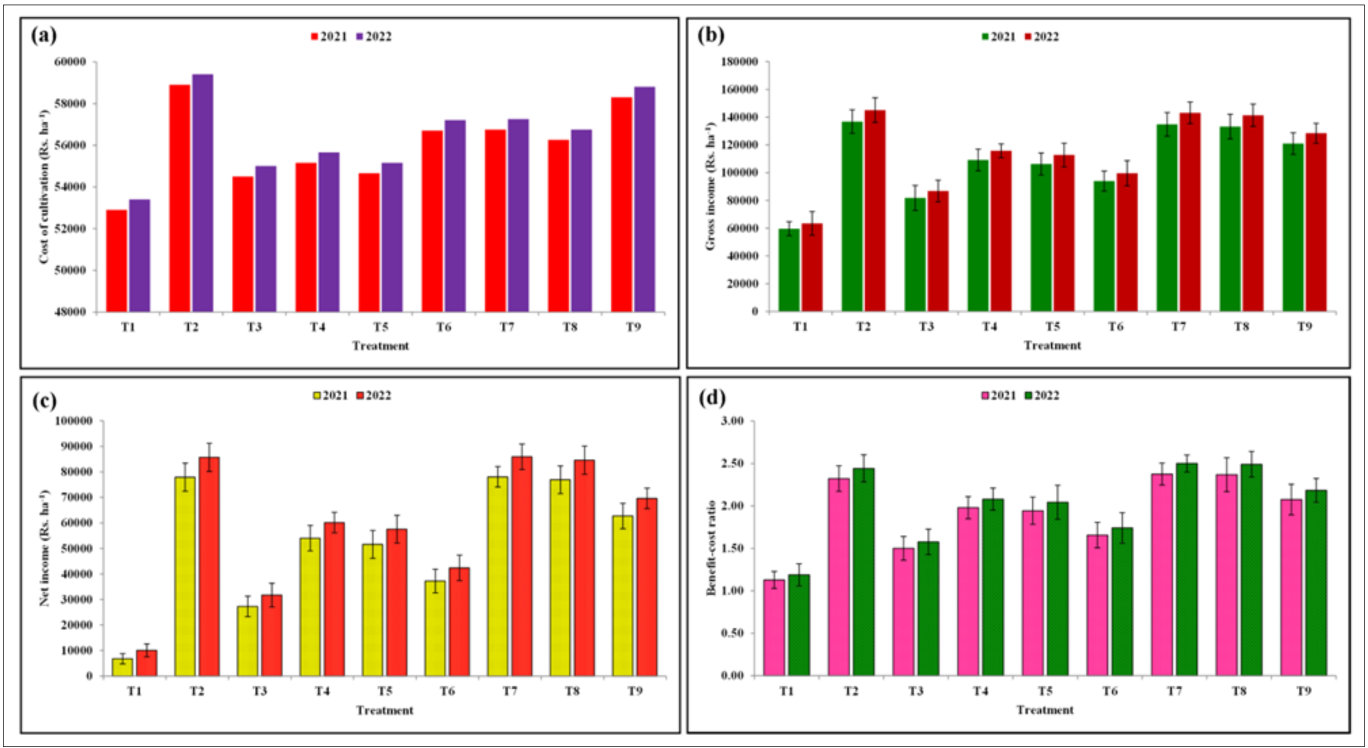

Fig. 2. Economics of maize as influenced by different weed management practices.

(a) Cost of cultivation; (b) Gross income; (c) Net income; (d) Benefit-cost ratio

*T_1 - Unweeded control; T_2 - Hand weeding twice at 15 and 30 DAS; T_3 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS; T_4 - PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_5 - PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_6 - PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS; T_7 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS; T_8 - PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS; T_9- PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of halosulfuron methyl at 67.5 g a.i ha^{-1} on 18 DAS

consistent with another study which reported that hand weeding twice at 20 and 40 DAS recorded the highest grain yield (2803 kg ha^{-1}) of maize as compared to weedy check (1394 kg ha^{-1}) and sole application of herbicides (1638-2447 kg ha^{-1}) (34). Besides, the higher nutrient absorption by well-proliferated root system caused by hand weeding might have increased the maize photosynthetic leaf area (by 73.01 % and 68.99 %) and total dry matter production (by 72.16 % and 72.60 %) which resulted in the highest grain yield (3) (Table 2). This was also favoured by reduced nutrient uptake by weeds. In this line, a previous study reported that the negative linear relationship between the nutrient (NPK) uptake by weeds and the grain yield of maize in which the maize grain yield was declined (N by 37 kg ha^{-1}, P by 283 kg ha^{-1}and K by 427 kg ha^{-1}) with each unit (kg ha^{-1}) increase of NPK in weeds (35,36). Nevertheless, hand weeding twice at 15 and 30 DAS (T_2) was on par with the PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1}on 18 DAS (T_7) and PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of tembotrione at 120 g a.i ha^{-1} on 18 DAS (T_8). The reduction in weed infestation with successive application of herbicides had contributed to the increased nutrient uptake and growth of maize which resulted in comparatively superior performance compared to other with either pre/PoE herbicide application (37). Similarly, a study reported higher biomass yield (by 49.74 %), grain yield (81.07 %) and water productivity (77.85 %) of maize with atrazine at 1.0 kg ha^{-1} (PE) followed by tembotrione at 0.10 g ha^{-1} (PoE) over the weedy check (38). However, 100 grain weight remained significantly unchanged.

Besides, hand weeding has several constraints like lack of labour facilities at the right time, unfavourable weather conditions, regeneration of weeds and higher cost of cultivation (39,40). Likewise in our study, though the gross income (₹136808 and 145095 ha^{-1}) was highest with T_2, the net income (₹78060 and 85901 ha^{-1}) and B-C ratio (2.38 and 2.50) were highest with T_7 due to the highest cost of cultivation caused by labour-intensive hand weeding (Fig. 2a–d). Further, it was followed by T_8. Hence, the sequential application of pre (atrazine at 1 kg a.i ha^{-1} on 3 DAS) and post (topramezone at 25.2 g a.i ha^{-1} or tembotrione at 120 g a.i ha^{-1} on 18 DAS) emergence herbicides (T_7/T_8) at right time was economically versatile and feasible.

Conclusion

Weed management strategies significantly impact maize yield and post-harvest nutrient balance. Our findings indicated that maize performed superior with hand weeding twice at 15 and 25 DAS. On the contrary, the residual nutrient balance in soil appeared highest with unweeded control due to reduced crop uptake, not actual soil enrichment, while it was lowest with hand weeding due to the highest crop uptake. Whereas, hand weeding was on par with the sequential application of pre (atrazine at 1 kg a.i ha^{-1} on 3 DAS) and post (topramezone at 25.2 g a.i ha^{-1} or tembotrione at 120 g a.i ha^{-1} on 18 DAS) emergence herbicides in weed control, maize growth, nutrient uptake, post-harvest nutrient balance, net gain of soil available nutrients and yields. However, based on the economics, PE application of atrazine at 1 kg a.i ha^{-1} on 3 DAS + PoE application of topramezone at 25.2 g a.i ha^{-1} on 18 DAS could be a better choice for achieving higher net returns and benefit-cost ratio in maize.

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Authors' contributions

SE participated in the design of the study, supervised the whole research and helped in compiling the manuscript. BMR carried out the field experiment, collection and analysis of data. SJ and SMSK participated in data analysis and edited the manuscript. SJP and SRV validated, reviewed and edited the manuscript. ES and SM analysed the data, edited and drafted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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