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RESEARCH ARTICLE

Enhancing growth, yield and nutrient use efficiency in hybrid maize through integrated nutrient and weed management strategies

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Abstract

Maize is a nutrient-demanding crop and weed competition during the critical growth stages can result in yield losses ranging from 28 to 100 %. Addressing this issue requires research focused on integrating innovative agronomic strategies. Therefore, 2 years (*kharif* 2020 and 2021) field experiments were conducted with different nutrient and weed management strategies to investigate their combined effect on maize. Nutrient management strategies (M) were included as main-plots, whereas weed management strategies (S) in sub-plots under split-plot design with 3 replications. The findings indicated that application of 187.5 kg N from urea + 62.5 kg N supplementation from press mud + $ZnSO_4$ at 37.5 kg/ha increased the uptake of N (by 35.56 %), P (27.36 %), K (33.84 %) and Zn (52.18 %), apparent N recovery (66.35 %) and grain yield (43.97 %) over the application of 250 kg N from urea. Similarly, hand hoeing at 15 and 30 days after sowing (DAS) had increased grain yield by 81.53 %, favoured by higher nutrient uptake and growth. Further, application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha in conjugation with hand hoeing at 15 and 30 DAS recorded the highest grain (7160 and 7490 kg/ha) and stover (10870 and 11620 kg/ha) yields during both the years. Subsequently, it was accompanied by application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha combined with pre-emergence (PE) application of atrazine at 1.0 kg a.i./ha at 3 DAS + post-emergence (PoE) application of topramezone at 25.2 g a.i./ha at 18 DAS with the highest net returns and benefit-cost ratio. Therefore, integrated urea (187.5 kg N) + press mud (62.5 kg N) + $ZnSO_4$ (37.5 kg/ha) application with PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS) as a weed management strategy could improve maize yield with higher economic viability.

Keywords: herbicides; maize; nutrient uptake; nutrient use efficiency; press mud; topramezone

Introduction

Maize (*Zea mays* L.) is a widely adaptable multipurpose cereal crop pivotal in global agriculture. It is cultivated in over 170 countries, with an annual production of 1157 million tons across 200.45 million ha, achieving an average productivity of 5.78 t/ha (1). Since maize is a heavy feeder of nutrients, its productivity depends on efficient nutrient management strategies. Therefore, it is necessary to improve the plant nutrient supply system by integrating chemical fertilizers with organic manures. The efficiency of maize grain production per unit of nitrogen fertilizer applied depends on the uptake from both fertilizer and soil nitrogen and its utilization during grain filling by enhanced net assimilation (2, 3). As nitrogen is the most limiting nutrient, ensuring its supply and other essential nutrients is crucial to maintaining soil fertility supporting sustained high maize production (4, 5).

Restoring organic matter in agricultural soils is crucial for enhancing crop production potential, sustaining biological health and maintaining soil carbon levels (6). Farmyard manure (FYM) is a widely used organic amendment that supplies essential plant nutrients. Additionally, recycling industrial by-products, such as press mud, serves as a waste management solution and a valuable soil amendment. Press mud application improves the soil structure nutrient availability and increases water-holding capacity. For instance, applying press mud at 12.5 t/ha with 75 % RDF increased the maize grain yield by 110 % and stover yield by 121 %, favouring the higher uptake of nutrients (7). Among the micronutrients, zinc is an essential component of various enzyme systems and is vital in plant metabolism, protein synthesis and attaining the potential crop yield. Zinc deficiency results in shorter internodes, decreased leaf size and yield (8). Globally, 50 % of the area under cereal cultivation is low in available Zn (9, 10).

Moreover, recent studies indicated that higher growth and yield of maize are associated with applying $ZnSO_4$ at 25 kg/ha along with the recommended dose of fertilizers (11, 12).

Yield losses in maize due to inadequate weed management during critical crop-weed competition stages range from 28 - 100 % (13, 14). Factors such as wider row spacing, slower initial growth and higher quantity of fertilizer application in maize create favourable conditions for excessive weed growth, ultimately reducing grain yield (15). Regardless of the situation, herbicides play a crucial role in weed management, offering timely and cost-effective control compared to manual weeding (16, 17). It is essential to use a mixture of herbicides with divergent modes of action to reduce alteration and resistance in the weed control spectrum (18). Sequentially applying pre (PE) and post emergence (PoE) new generation herbicide molecules at the time of temporal variation may help avoid weeds throughout the maize growth stages. The sequential use of atrazine at 1.0 kg a.i./ha (PE) followed by tembotrione at 125 g a.i./ha (PoE) registered maizes' lowest weed dry biomass (19). Similarly, PE application of atrazine at 0.5 kg a.i./ha followed by topramezone at 25.2 g a.i./ha (PoE) significantly reduced the weed density (20). Usage of PE herbicides, especially atrazine and PoE herbicides *viz.,* topramezone, tembotrione and halosulfuron methyl, assumes greater importance given their effectiveness during initial and later stages of weed emergence. Though the previous studies have solitarily focused on the nutrient and weed management practices in maize, there is still a lack of insightful studies on their combined use. By considering these facts, we hypothesized that a combination of ideal nutrient and weed management strategies could achieve the higher production potential of maize with increased nutrient use efficiencies, bringing a novel contribution to maize research. In light of the above facts, field experiments were conducted for 2 consecutive years (*kharif* 2021 and 2022) to find a suitable integrated nutrient and weed management with the objectives of studying the combined effect of different nutrient and weed management strategies on (i) growth and yield of maize and (ii) nutrient uptake and post-harvest available soil nutrient status and (iii) nutrient use efficiencies of maize.

Materials and Methods

Experimental site details

Field experiments were conducted during the *kharif* seasons (June to September) of 2021 and 2022 at B. Mutlur, Chidambaram, Tamil Nadu, India (11.46 °N, 79.70 °E; 5.8 m above mean sea level). The experimental site has a moderately warm climate with hot summers. During the cropping seasons, weekly mean maximum temperature ranged from 38.6 - 32.6 °C (2021) and 37.8 - 32.3 °C (2022), while weekly mean minimum temperature ranged from 26.2 - 23.1 °C (2021) and 25.2 - 23.6 °C (2022). Relative humidity ranged from 79 - 90 % (2021) and 64 - 81 % (2022). The total rainfall recorded was 385.4 mm in 2021 and 269.1 mm in 2022. The soil at the experimental site is clayey loam, with low available nitrogen (227.2 kg/ha), medium available phosphorus (18.6 kg/ha), high available potassium (324.5 kg/ha) and low available zinc (0.52 mg/kg).

Experimental design and field management

A split-plot design with 3 replications was used for the experiment. Nutrient management strategies (M) were assigned to main plots, consisting of M_1: 250 kg N from urea, M_2: M_1 + 37.5 kg $ZnSO_4$, M_3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg $ZnSO_4$ and M_4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg $ZnSO_4$. Whereas Weed management strategies (S) were assigned to sub-plots, including S_1: Unweeded control, S_2: Hand hoeing at 15 and 30 DAS, S_3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S_4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S_5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS). The experimental area was cleared of rice stubble and weeds and the soil was prepared to a fine tilth before sowing the maize hybrid Ankur Aditya on June 7, 2021 and June 4, 2022. As per the treatment schedule, the recommended quantity of nutrients (250:75:75 kg NPK/ha) were supplied from urea $[CO(NH_2)_2]$, single super phosphate $[Ca(H_2PO4)_2]$ and muriate of potash (KCl), respectively. Further, as per treatment requirement, FYM (contained 0.56 % N, 0.21 % P and 0.48 % K as analyzed), press mud (contained 2.12 % N, 0.56 % P and 1.52 % K (Table 2) and $ZnSO_4.7H_2O$ (contained

Table 1. Weekly mean weather data observed during the cropping period in 2021 and 2022

Standard	Month	Mean temperature (°C)				Relative humidity (%)		Rainfall (mm)		Number of rainy days		Bright	
		Minimum		Maximum									
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
23	June 4 - 10	25.6	25.1	36.7	37.3	81	64	19.2	8.6	1	1	7.4	6.5
24	June 11 – 17	26.2	24.6	37.0	37.8	79	67	5.4	28.0	1	1	6.1	7.5
25	June 18 – 24	24.9	24.5	37.0	35.2	81	68	12.2	0	1	-	5.9	5.0
26	June 24 – July 1	25.4	25.0	35.8	37.2	81	69	0.2	5.8	-	1	6.8	6.3
27	July 2 - 8	24.4	24.7	36.4	35.6	84	66	53.2	23.6	2	3	8.6	3.7
28	July 9 - 15	25.2	25.2	34.1	35.5	85	65	18.8	01.0	1	-	3.0	4.3
29	July 16 - 22	24.9	24.4	34.8	36.0	82	70	1.6	22.4	-	1	5.0	7.2
30	July 23 - 29	24.3	23.3	36.1	34.4	87	73	48.2	50.5	2	3	7.7	6.4
31	July 30 - Aug. 5	24.2	24.3	38.6	33.2	81	78	0	13.0	-	2	7.3	3.3
32	Aug. 6 - 12	24.0	24.0	36.3	34.3	83	67	4.8	0	1	-	8.2	6.1
33	Aug. 13 – 19	23.8	23.9	34.3	36.2	86	69	122.4	47.4	2	1	2.8	7.5
34	Aug. 20 – 26	24.2	24.7	32.6	33.9	88	76	1.8	38.6	-	3	4.2	4.5
35	Aug. 27 - Sep. 2	23.9	23.6	34.1	32.3	90	81	14.8	27.0	2	2	3.2	4.1
36	Sep. 3 – 9	23.1	23.7	33.3	33.5	87	74	52.8	1.2	3	-	3.7	5.0
37	Sep. 10 – 16	24.2	24.9	36.1	34.9	81	70	14.2	2.0	1	-	6.2	6.2
38	Sep. 17 – 23	23.6	24.3	34.2	35.3	87	68	15.8	0	1	-	5.4	6.4
Total		24.5	24.4	25.5	35.2	83.9	70.3	385.4	269.1	18	18	-	-

Table 2. Characteristics of press mud

Characteristic	Values
Nutrient content	N: 2.12 %, P: 0.56 %, K: 1.52 %
Moisture content	63 %
pH level	7.21
Organic matter	45 % (on a dry weight basis)
Colour	Dark brown
Odor	Pungent
Cation exchange capacity	200 mmol/kg

21.0 % Zn and 15 % S) were applied after formation of layout in the field experiment. Half the quantity of N and the complete quantity of P and K fertilizers were used initially when sowing. The remaining half amount of N was top dressed at knee height stage of the crop. Irrigation was given regularly at 50 % of available soil moisture depletion. As per the treatments, the required quantity of formulated herbicide products was diluted in 500 L of water/ha and applied as a pre-emergence (3 DAS)/post-emergence herbicides (18 DAS) using a knapsack sprayer with flood jet nozzle.

Weed growth

Total weed density and weed dry weight

The total weed density at 45 DAS was counted in each plot from 4 randomly selected areas (0.25 m^2) using 0.5 m × 0.5 m quadrate and the mean was calculated and expressed as number m^{-2}. Later, the collected samples were later dried out in a hot air oven at 65 °C until a constant weight was attained and dry weight was expressed in g/m^2.

Weed control indices

The formulae used for calculating the weed control indices are presented in Table 3.

Plant growth and yield

The plant height and total dry matter production were recorded at the harvest stage of the crop. The above-ground plant parts were collected, shade-dried for 2 days and dried in a hot air oven at 65 °C till obtaining a steady weight. The leaf area index (LAI) was recorded at the flowering stage.

Plant nutrient uptake studies

The hot air oven-dried plant samples at harvest stage were crushed, powdered and digested with acids for analyzing nutrient content *viz.,* total nitrogen by Microkjeldhol technique, phosphorus by calorimetric technique and potassium using flame photometer (25, 26). Meanwhile, the zinc content was evaluated using the atomic absorption spectrophotometer (27). Nutrient uptake by crop *viz.,* NP and K were calculated with formula (Eqn. 1),

$$\text{Nutrient uptake (kg/ha)} = \frac{\text{Nutrient content in sample (\%) x Dry matter production(kg/ha)}}{100} \quad \text{(Eqn. 1)}$$

Whereas Zn uptake was calculated by formula (Eqn. 2),

$$\text{Zinc uptake (mg/ha)} = \frac{\text{Nutrient content (ppm) x Dry matter production (kg/ha)}}{1000} \quad \text{(Eqn. 2)}$$

Nutrient use efficiencies

The Agronomic efficiency (AE) is the response in yield per unit input as indicated by kg of grain per kg of N was calculated with the formula (Eqn. 3) (28),

Table 3. Characteristics of press mud

S. No	Parameter	Formula	Reference
1	Weed control efficiency (WCE)	$\text{WCE (\%)} = \frac{W_{PC} - W_{PT}}{W_{PC}} \text{ X } 100$	(21)
2	Weed control index (WCI)	$\text{WCI (\%)} = \frac{W_C - W_T}{W_C} \text{ X } 100$	(22)
3	Weed persistence index (WPI)	$\text{WPI (\%)} = \frac{W_T}{W_C} \text{ x } \frac{W_{PC}}{W_{PT}}$	(23)
4	Treatment efficiency index (TEI)	$\text{TEI} = \frac{\frac{Y_T - Y_C}{Y_C}}{\frac{W_T}{W_C}}$	(24)
5	Crop resistance index (CRI)	$\text{CRI} = \frac{D_T}{D_C} \text{ x } \frac{W_C}{W_T}$	(23)

Where WPC – Weed population in control (unweeded) plot and WPT - Weed population in the treated plot, WC - Weed dry weight in the control plot, WT - Weed dry weight in treated plot, DC - Dry matter produced by the crop in control plot and DT - Dry matter produced by the crop in treated plot, YT - Yield of treated plot, YC - Yield of treated plot (unweeded plot), WC - Weed dry weight in control plot and WT - Weed dry weight in treated plot.

Agronomic efficiency (kg grain/kg N applied=

$$\frac{\text{Grain yield in fertilized plot (kg/ha) - Grain in unfertilized plot (kg/ha)}}{\text{Quantity of fertilizer N applied (kg/ha)}} \quad \text{(Eqn. 3)}$$

Apparent nitrogen recovery (ANR), also known as recovery fraction was estimated with the formula (Eqn. 4) (29),

$$\text{Apparent recovery N (\%)} = \frac{U_i - U_o}{Ni} \times 100 \quad \text{(Eqn. 4)}$$

Where, U_i - uptake of N in particular treatment (kg/ha); U_0 - Uptake of N in unfertilized plot (kg/ha); N_i - Quantity of N applied for the treatment (kg/ha)

Partial factor productivity is the kg grain produced per unit of kg N applied and was calculated using the formula (Eqn. 5) (30),

$$\text{Partial factor productivity (kg grain/kg N)} = \frac{\text{kg grain}}{\text{kg N applied}} \quad \text{(Eqn. 5)}$$

Soil nutrient analysis

After crop harvest, the soil samples collected from experimental plots (0 - 30 cm depth) were processed and sieved by a 2 mm sieve for further analysis. Soil available N was analyzed by the alkaline potassium permanganate method, available P was determined with the ascorbic acid blue technique using a calorimeter and available K was determined with neutral standard ammonium acetate method using a flame photometer (26, 31, 32). At the same time, available Zn was determined with the DTPA extractable method using an atomic absorption spectrophotometer (27).

Statistical analysis

The collected data were subjected to a normality test before analyzing variance. As the data on total weed density and weed dry weight was not found to be normal, the square root transformation ($\sqrt{x+0.5}$) was done to normalize the data. Further, analysis of variance (ANOVA) was determined separately for 2 years under a split-plot design with 3 replications. The significant difference between the treatments was tested with Duncans' multiple range test (DMRT) test ($\alpha = 0.05$) using GrapesAgri1 Version 1.1.0 (33). Later, the principal component analysis was done to find the association between weed control indices, nutrient uptake and maize yield.

Results

Weed growth and weed control indices

Nutrient management strategies did not significantly influence weed growth or weed control indices in either year of the maize experiment (Table 4). However, weed management strategies had a significant effect ($p < 0.05$), with the highest weed control efficiency (86.15 % and 89.), weed control index (86.09 % and 89.49 %), treatment efficiency index (5.87 and 7.98) and crop resistance index (12.55 and 17.32) and the lowest total weed density (27.44/m^2 and 17.34/m^2) and total wed dry weight (24.36/m^2 and 14.88/m^2) during 2020 and 2021 respectively with the hand hoeing at 15 and 30 days after sowing; DAS (S_2). Whereas this treatment was on par with pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) (S_5). Considering the interaction effects, the highest treatment efficiency index (7.74 and 10.91) and crop resistance index (14.94 and 20.94) were recorded with the application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha and hand hoeing at 15 and 30 days after sowing; DAS (M_4S_2) (Table S1).

This was followed closely by M_4 integrated with PE atrazine (1.0 kg a.i./ha at 3 DAS) and PoE topramezone (25.2 g a.i./ha at 18 DAS) (M_4S_5). The lowest weed control indices were observed in M_1S_3 (250 kg N from urea + PE atrazine at 3 DAS + one hand hoeing at 30 DAS), which was statistically similar to M_1S_4 (250 kg N from urea + PoE topramezone at 18 DAS + one hand hoeing at 30 DAS.

Nutrient uptake of maize

Nutrient and weed management strategies had a significant effect ($P < 0.05$) on nutrient uptake of maize (Table 5). Among the nutrient management strategies, application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha (M_4) recorded the maximum nutrient uptake *viz.,* N (147.55 and 153.67 kg/ha), P (30.37 and 34.25 kg/ha), K (100.70 and 103.71.0 kg/ha) and Zn (1.36 and 1.44 mg/kg). At the same time, the minimum nutrient uptake was noticed with the application of 250 kg N from urea (M_1). Likewise, about weed management strategies, S_2 recorded significantly the highest uptake of N (149.72 and 155.53 kg/ha), P (30.62 and 33.73 kg/ha), K (101.57 and 101.62 kg/ha) and Zn (1.36 and 1.46 mg/kg). At the same time, the lowest was with unweeded control (S_1). Similarly among the interaction effects, application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha + hand hoeing twice at 15 and 30 DAS (M_4S_2) recorded the utmost nutrient uptake *viz.,* N (172.55 and 177.07 kg/ha), P (33.58 and 41.08 kg/ha), K (117.71 and 124.65 kg/ha) and Zn (1.61 and 1.70 mg/kg) (Table S2). However, it was on par with the application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha and PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS) (M_4S_5). Moreover, the lowest nutrient uptake was observed with 250 kg N from urea + unweeded control (M_1S_1).

Growth and yield of maize

The key growth characteristics of maize were significantly ($P < 0.05$) affected by the nutrient and weed management strategies (Table 6). Among the nutrient management strategies, M_4 recorded superior growth parameters *viz.,* plant height (201.64 and 215.82 cm), leaf area index (LAI; 5.48 and 5.82) and dry matter production (11478 and 12040

Table 4. Effect of integrated nutrient and weed management strategies on weed growth and weed control indices in maize

Treatment	Total weed density (no./m^2)		Total weed dry weight (g/m^2)		Weed control efficiency (%)		Weed control index		Weed persistence index		Treatment efficiency index		Crop resistance index	
	At 45 DAS													
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Nutrient management strategies (M)														
M_1	8.35a* (69.23)	7.20a† (51.39)	8.08a (64.72)	6.88a (46.82)	63.93a	67.96a	64.33a	68.19a	0.97a	0.98a	2.71d	3.72d	7.57d	10.02d
M_2	8.31a (68.50)	7.16a (50.73)	7.93a (62.41)	6.80a (45.71)	64.17a	68.26a	64.48a	68.45a	0.98a	0.98a	3.19c	4.49c	8.55c	11.80c
M_3	8.26a (67.76)	7.11a (49.99)	7.85a (61.19)	6.62a (43.30)	64.47a	68.60a	64.81a	68.85a	0.98a	0.98a	4.49b	5.82b	9.78b	13.84b
M_4	8.21a (66.97)	7.05a (49.26)	7.72a (59.05)	6.47a (41.34)	64.79a	68.96a	65.05a	69.21a	0.98a	0.97a	5.45a	7.60a	10.97a	15.59a
S.Em. ±	0.04	0.03	0.04	0.05	0.56	0.60	0.56	0.60	0.02	0.02	0.04	0.05	0.07	0.10
Weed management strategies (S)														
S_1	13.84a (191.00)	12.65a (159.54)	13.25a (174.99)	11.91a (141.34)	-	-	-	-	-	-	-	-	-	-
S_2	5.29c (27.44)	4.22c (17.34)	4.99c (24.36)	3.92c (14.88)	86.15a	89.14a	86.09a	89.49a	0.97a	0.97a	5.87a	7.98a	12.55a	17.32a
S_3	6.92b (47.43)	5.41b (28.76)	6.59b (42.98)	5.07b (25.22)	75.77b	81.98b	75.45b	82.17b	0.99a	0.99a	2.10c	2.98d	5.99c	8.51c
S_4	6.89b (46.94)	5.37b (28.35)	6.54b (42.25)	5.03b (24.76)	76.08b	82.24b	75.86b	82.50b	0.98a	0.98a	2.26c	3.20c	6.19c	8.82c
S_5	5.32c (27.77)	4.27c (17.74)	5.01c (24.64)	3.97c (15.27)	85.94a	88.89a	85.93a	89.21a	0.97a	0.97a	5.62b	7.47b	12.15b	16.59b
S.Em. ±	0.07	0.06	0.07	0.08	0.56	0.59	0.56	0.59	0.02	0.03	0.03	0.05	0.07	0.10
Source of variation									**P value (< 0.05)**					
M	0.12	0.13	0.16	0.15	0.59	0.54	0.68	0.51	0.52	0.54	<0.0001	<0.0001	<0.0001	<0.0001
S	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.56	0.57	<0.0001	<0.0001	<0.0001	<0.0001
M × S	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.58	0.60	<0.0001	<0.0001	<0.0001	<0.0001

† Different lowercase letters indicate significant differences between treatments (P < 0.05). *Data was transformed using square root transformation (√x+0.5) and values in parenthesis indicate the original value. M1: 250 kg N from urea, M2: M1 + 37.5 kg ZnSO4, M3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg ZnSO4, M4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg ZnSO4, S1: Unweeded control, S2: Hand hoeing at 15 and 30 DAS, S3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS).

kg/ha) and yield such as grain (6066 and 6278 kg/ha) and stover (9320 and 9882 kg/ha) yield of maize. At the same time, the lowest was with M_1. Similarly, under the different weed management strategies, S_2 recorded maximum plant height (200.60 and 214.94 cm), LAI (5.53 and 5.87), dry matter production (11631 and 12133 kg/ha), grain (6097 and 6312 kg/ha) and stover (9372 and 9927 kg/ha) yields. However, it was at par with S_5. At the same time, S_1 recorded the lowest growth attributes and yield. Considering the interaction effects, the plant height (229.75 and 245.82 cm), LAI (5.97 and 6.28), dry matter production (13376 and 14165 kg/ha) and grain (6097 and 6312 kg/ha) and stover (9372 and 9927 kg/ha) yields were the highest with M_4S_2 (Table S3). However, it was on par with M_4S_5. Consequently, the lowest growth attributes and yield were observed with M_1S_1.

Nutrient use efficiencies

Nutrient and weed management strategies had a profound effect (P < 0.05) on nutrient use efficiencies of maize (Table 5). Among the nutrient management strategies, M_4 registered the highest agronomic efficiency (15.00 and 15.90 kg grain/kg N applied), apparent nitrogen recovery (38.41 and 40.86 %) and partial factor productivity (24.26 and 25.04 kg grain/kg N applied). The trend was observed in $M_4>M_3>M_2>M_1$. Similarly, under different weed management practices, the highest agronomic efficiency (15.15 and 16.03 kg grain/kg N applied), apparent nitrogen recovery (39.27 and 41.60 %) and partial factor productivity (24.38 and 25.25 kg grain/kg N applied) were recorded with S_2. It was followed by other weed management practices in the order of $S_5>S_4>S_3>S_1$. Likewise, among interactions, M_4S_2 recorded the highest agronomic efficiency (19.37 and 20.74 kg grain/kg N applied), apparent nitrogen recovery (48.41 and 50.22 %) and partial factor productivity (28.63 and 29.96 kg grain/kg N applied) (Table S2). At the same time, the lowest values were recorded under M_1S_1.

Post-harvest available nutrients

The status of the post-harvest available N, P and K, except available Zn remained significantly unaffected by different nutrient management strategies (Fig. 1a-d). The highest available zinc (0.69 and 0.65 mg/kg) was observed under M_4. Regarding the weed management strategies evaluated, the highest post-harvest nutrient available N (225.14 and 224.73 kg/ha) and K (322.07 and 321.07 kg/ha) status were registered under M_1. However, it did not significantly impact the available phosphorus (P). Contrastingly, the highest available Zn (0.65 and 0.61 mg/kg) was recorded under S_3, which was in the trend of $M_4>M_3>M_2>M_1$. At the same time, S_2 recorded the lowest available N, P and K. However, it was on par with S_5. The interaction effects did not differ significantly on post-harvest available N, P and K (Table S4). Whereas available, Zn was significantly the

Table 5. Effect of integrated nutrient and weed management strategies on nutrient uptake and nutrient use efficiencies of hybrid maize

Treatment	Nutrient uptake								Nutrient use efficiencies					
	Nitrogen (kg/ha)		Phosphorus (kg/ha)		Potassium (kg/ha)		Zinc (mg/kg)		Agronomic efficiency (kg grain/ kg N/ha)		Apparent N recovery (%)		Partial Factor productivity (kg grain/ kg N/ha)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Nutrient management strategies (M)														
M_1	109.33^{d}†	112.85^{d}	25.02^{d}	25.68^{d}	74.81^{d}	77.93^{d}	0.89^{d}	0.95^{d}	7.68^{d}	8.33^{d}	23.12^{d}	24.53^{d}	16.97^{d}	17.31^{d}
M_2	121.51^{c}	126.02^{c}	26.67^{c}	27.76^{c}	82.89^{c}	84.26^{c}	1.09^{c}	1.17^{c}	9.95^{c}	10.66^{c}	27.99^{c}	29.80^{c}	19.33^{c}	19.72^{c}
M_3	134.69^{b}	140.52^{b}	28.71^{b}	30.24^{b}	91.96^{b}	91.08^{b}	1.23^{b}	1.31^{b}	12.72^{b}	13.45^{b}	33.27^{b}	35.60^{b}	21.94^{b}	22.58^{b}
M_4	147.55^{a}	153.67^{a}	30.37^{a}	34.25^{a}	100.70^{a}	103.71^{a}	1.36^{a}	1.44^{a}	15.00^{a}	15.90^{a}	38.41^{a}	40.86^{a}	24.26^{a}	25.03^{a}
S.Em. ±	0.84	0.87	0.17	0.20	0.57	0.61	0.0079	0.0085	0.09	0.10	0.23	0.24	0.13	0.14
Weed management strategies (S)														
S_1	88.71^{d}	92.50^{d}	21.85^{d}	22.65^{c}	63.38^{d}	68.67^{c}	0.70^{c}	0.76^{c}	4.36^{e}	4.72^{e}	14.87^{e}	16.39^{e}	13.57^{c}	13.74^{d}
S_2	149.72^{a}	155.53^{a}	30.62^{a}	33.73^{a}	101.57^{a}	101.62^{a}	1.36^{a}	1.46^{a}	15.15^{a}	16.03^{a}	39.27^{a}	41.60^{a}	24.38^{a}	25.25^{a}
S_3	127.76^{c}	131.92^{c}	27.67^{b}	28.62^{b}	86.13^{c}	87.30^{b}	1.15^{b}	1.22^{b}	11.02^{d}	11.89^{e}	30.49^{d}	32.16^{d}	20.38^{b}	20.91^{c}
S_4	129.75^{c}	134.13^{c}	28.04^{b}	29.08^{b}	87.75^{c}	88.21^{b}	1.17^{b}	1.24^{b}	11.35^{c}	12.26^{c}	31.29^{c}	33.04^{c}	20.76^{b}	21.28^{c}
S_5	145.42^{b}	152.27^{cb}	30.29^{a}	33.37^{a}	99.14^{b}	100.44^{a}	1.35^{a}	1.44^{a}	14.82^{b}	15.52^{b}	37.56^{b}	40.29^{b}	24.03^{a}	24.63^{b}
S.Em. ±	0.90	0.93	0.19	0.21	0.61	0.63	0.0083	0.0088	0.08	0.09	0.22	0.24	0.14	0.15
Source of variation									**P value (<0.05)**					
M	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
S	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
M × S	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

†Different lowercase letters indicate significant differences between treatments (P < 0.05). M1: 250 kg N from urea, M2: M1 + 37.5 kg ZnSO4, M3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg ZnSO4, M4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg ZnSO4, S1: Unweeded control, S2: Hand hoeing at 15 and 30 DAS, S3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS).

Table 6. Effect of integrated nutrient and weed management strategies on growth and yield of hybrid maize

Treatment	Plant height at harvest (cm)		Leaf Area Index at flowering		Crop dry matter production at harvest (kg/ha)		Grain yield (kg/ha)		Stover yield (kg/ha)	
	2021	2022	2021	2022	2021	2021	2021	2022	2021	2022
Nutrient management strategies (M)										
M_1	153.44^{d}†	165.02^{d}	4.77^{d}	5.08^{d}	8432^{d}	8435^{d}	4244^{d}	4329^{d}	6717^{d}	7196^{d}
M_2	169.13^{c}	182.13^{c}	4.96^{c}	5.29^{c}	9515^{c}	9598^{c}	4836^{c}	4932^{c}	7580^{c}	8052^{c}
M_3	185.6^{b}	199.42^{b}	5.24^{b}	5.56^{b}	10561^{b}	10937^{b}	5486^{b}	5648^{b}	8504^{b}	9002^{b}
M_4	201.64^{a}	215.82^{a}	5.48^{a}	5.82^{a}	11478^{a}	12040^{a}	6066^{a}	6278^{a}	9320^{a}	9882^{a}
S.Em. ±	1.136	1.21	0.03	0.03	65.26	69.11	34.86	36.39	53.06	56.34
Weed management strategies (S)										
S_1	129.37^{c}	139.14^{c}	4.47^{c}	4.80^{d}	6607^{c}	6703^{c}	3395^{c}	3440^{d}	5447^{c}	5890^{c}
S_2	200.60^{a}	214.94^{a}	5.53^{a}	5.87^{a}	11631^{a}	12133^{a}	6097^{a}	6312^{a}	9372^{a}	9927^{a}
S_3	178.60^{b}	191.95^{b}	5.03^{b}	5.36^{c}	10076^{b}	10160^{b}	5095^{c}	5229^{c}	7967^{b}	8472^{b}
S_4	179.26^{b}	192.87^{b}	5.10^{b}	5.44^{c}	10148^{b}	10330^{b}	5192^{b}	5320^{c}	8097^{b}	8605^{b}
S_5	199.54a	214.11^{a}	5.45^{a}	5.74^{b}	11525^{a}	11937^{a}	6010^{a}	6182^{b}	9267^{a}	9770^{a}
S.Em. ±	1.24	1.33	0.03	0.04	70.18	72.42	36.40	37.59	56.45	59.92
Source of variation						**P value (<0.05)**				
M	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
S	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
M × S	0.54	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

†Different lowercase letters indicate significant differences between treatments (P < 0.05). M_1: 250 kg N from urea, M_2: M_1 + 37.5 kg $ZnSO_4$, M_3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg $ZnSO_4$, M_4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg $ZnSO_4$, S_1: Unweeded control, S_2: Hand hoeing at 15 and 30 DAS, S_3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S_4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S_5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS).

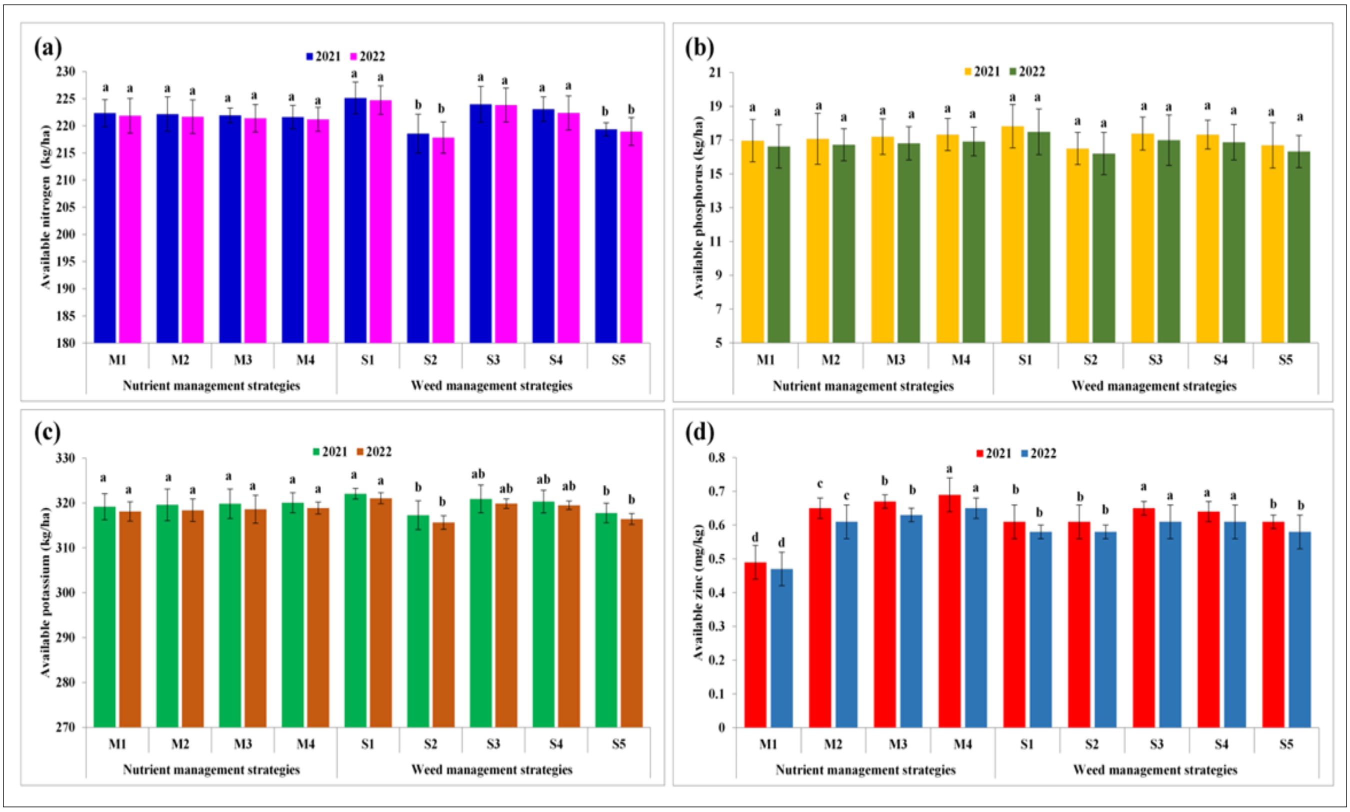


Fig. 1. Post-harvest available soil nutrient status after harvest of hybrid maize as influenced by different nutrient and weed management strategies; (a) Available nitrogen (kg/ha), (b) Available phosphorus (kg/ha), (c) Available potassium (kg/ha) and (d) Available zinc (mg/kg). M1: 250 kg N from urea, M2: M1 + 37.5 kg $ZnSO_4$, M3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg $ZnSO_4$, M4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg $ZnSO_4$, S1: Unweeded control, S2: Hand hoeing at 15 and 30 DAS, S3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS).

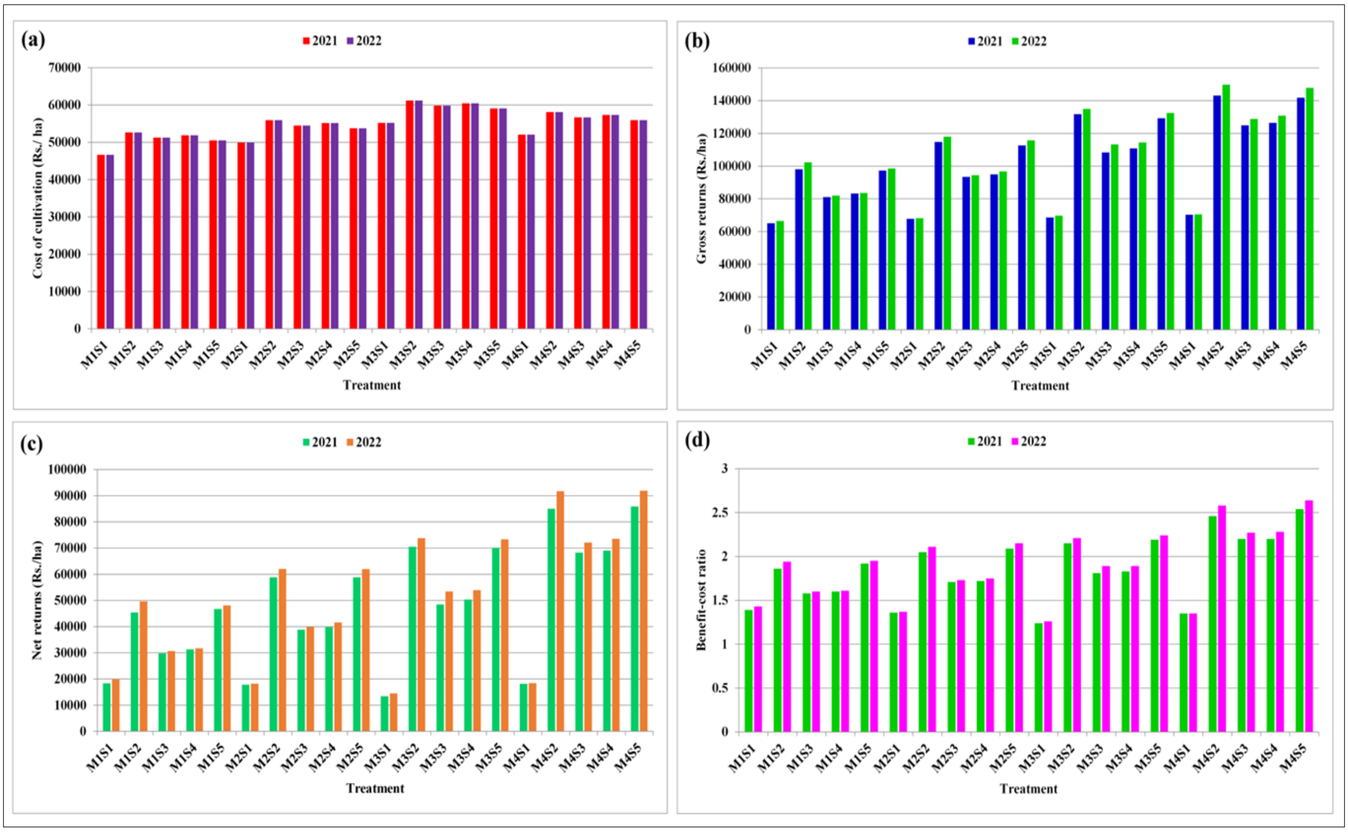


Fig. 2. Economics of maize as influenced by integrated nutrient and weed management strategies: (a) Cost of cultivation, (b) Gross returns (Rs/ha), (c) Net returns (Rs/ha) and (d) Benefit-cost ratio. M1: 250 kg N from urea, M2: M1 + 37.5 kg $ZnSO_4$, M3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg $ZnSO_4$, M4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg $ZnSO_4$, S1: Unweeded control, S2: Hand hoeing at 15 and 30 DAS, S3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS).

highest with M_4S_3 and M_4S_4 and lowest with M_1S_1 and M_1S_2.

Economics

The application of 75 % RDN + 25 % N from press mud + $ZnSO_4$ at 37.5 kg/ha + hand hoeing twice at 15 and 30 DAS (M_4S_2) registered the highest gross returns (Rs. 143140/ha and Rs. 149780/ha) during the years 2021 and 2022, respectively (Fig. 2b). However, application of 75 % RDN + 25 % N from press mud + $ZnSO_4$ at 37.5 kg/ha and PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE (topramezone at 25.2 g a.i./ha at 18 DAS) (M_4S_5) recorded the highest net returns (Rs. 85877/ha and Rs. 91897/ha) and benefit-cost ratio (2.54 and 2.64) (Fig. 2c-d). Whereas the lowest gross returns (Rs. 65000/ha and Rs. 66500/ha), net returns (Rs. 18346/ha and Rs. 19846/ha) and benefit cost-ratio (1.39 and 1.43) were obtained with the application of 100 % RDN + unweeded control (M_1S_1) during 2021 and 2022 respectively.

Association between weed control indices, nutrient uptake and maize yield

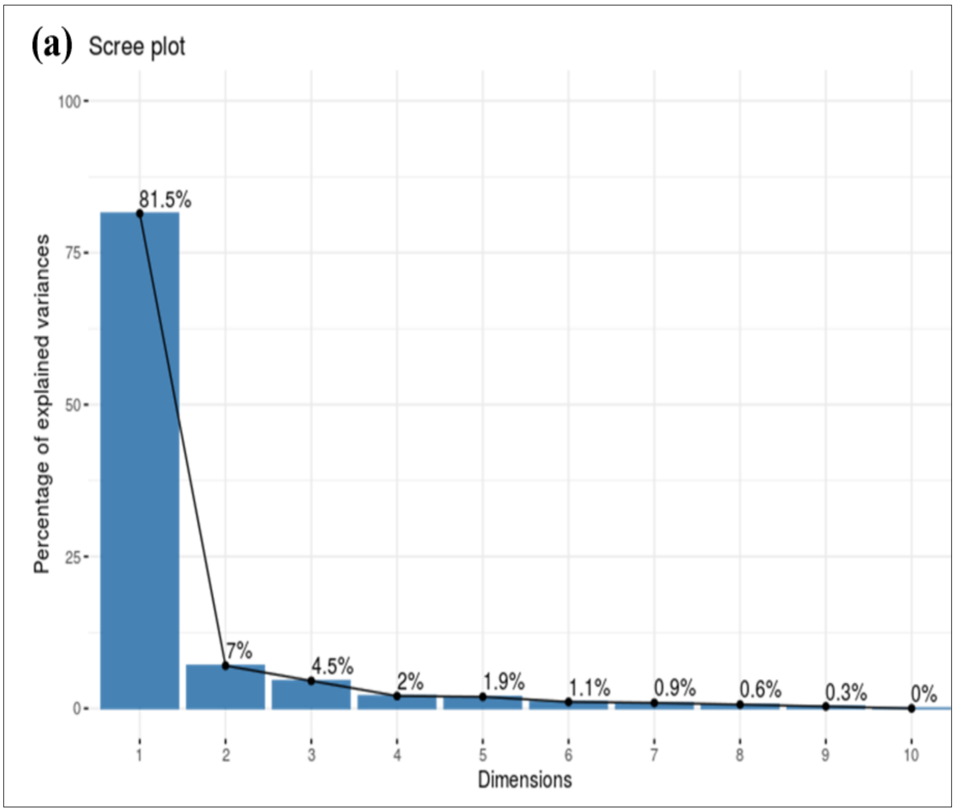
The association between the weed control indices, nutrient uptake and maize yield under integrated weed and nutrient management strategies was studied by the principal component analysis (PCA) (Fig. 3a-3c). The results revealed that the principal components PC1 (81.47 %) and PC2 (7.04 %) accounted for 88.51 % of the total variability in experimental results (Fig. 3a). The majority of variables like NPK and Zn uptake, grain yield (9.) and Stover yield (9.07 %) had contributed to the variation in PC1, whereas the variables like weed control index (WCI; 36.47 %) and weed control efficiency (WCE; 36.46 %) contributed towards PC2. Similarly, the variables like NPK and Zn uptake, grain yield (r = 0.93) and Stover yield (r = 0.90) had higher positive correlations with PC1, whereas WCE (r = 0.53) and WCI (r = 0.53) were moderately correlated with PC2 (Fig. 3b). Further, the bipolt analysis indicated that NPK and Zn uptake, treatment efficiency index (TEI), leaf area index (LAI), grain yield and stover yield showed a strong positive association with M_3S_4, M_3S_2, M_4S_5 and M_4S_2 highlighting the association of yield contributing traits (Fig. 3c).

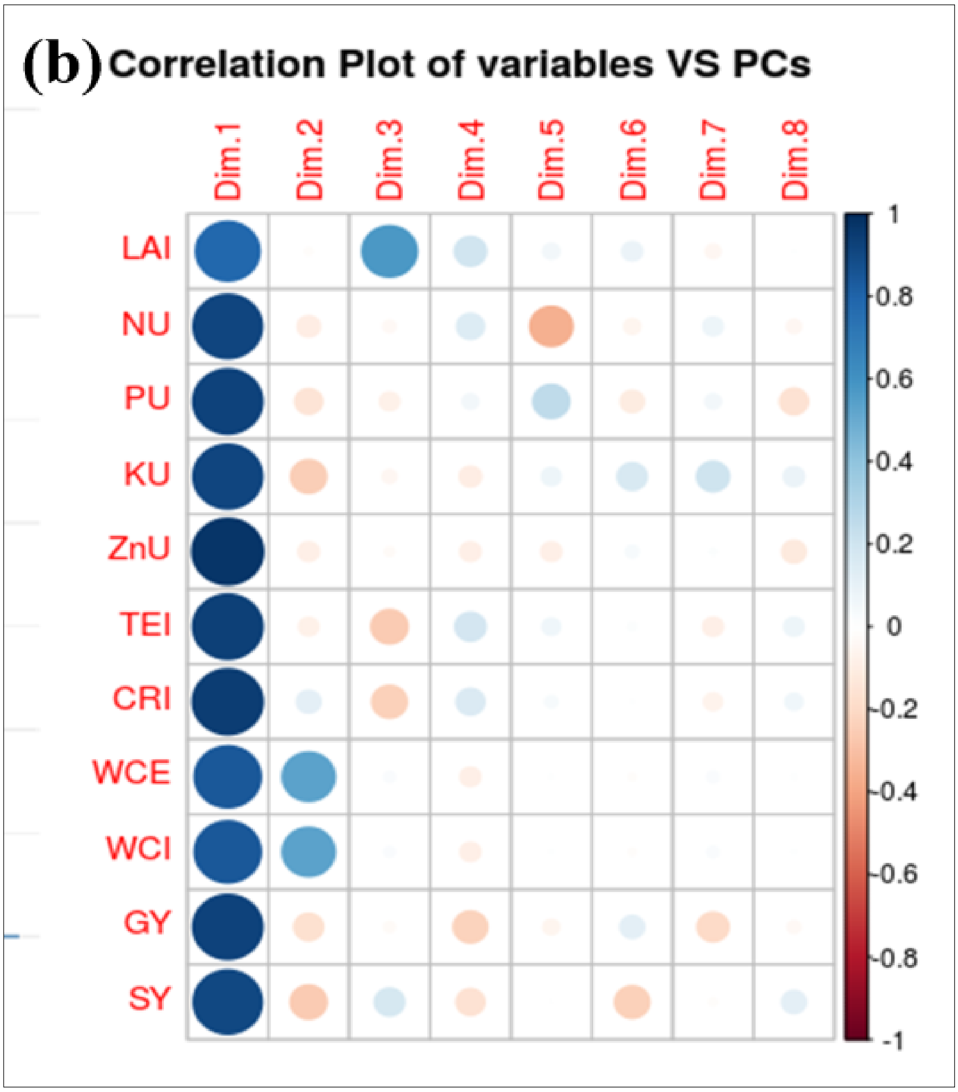
Discussion

Maize contributes approximately 30 % of global caloric intake, feeding nearly 4.5 billion people. A well-balanced nutrient management strategy is essential to sustain high grain and stover yields. Additionally, effective weed management, in combination with optimal nutrient application, is crucial for minimizing crop-weed competition and maximizing maize yield. This study examined the impact of integrated nutrient and weed management strategies on maize production and nutrient use efficiencies. Among the nutrient management strategies, the application of 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg $ZnSO_4$/ha resulted in a 42.93 - 45.02 % increase in grain yield and a 38.75 - 37.32 % increase in stover yield compared to 250 kg N from urea alone (Table 6). Adding organic matter through press mud enhances soil microbial diversity and activity, increasing soil organic matter mineralization and improving nitrogen availability (34).

Additionally, press mud improves P and K solubility, stimulating root absorption (35). Zn supplementation further enhances N and K utilization and facilitates photosynthates translocation, contributing to increased plant height, leaf area index (LAI) and dry matter production (Table 6) (36, 37). Besides, applying Zn, press mud and inorganic fertilizers might have triggered enzymatic activities and active plant metabolism, resulting in maximum plant height, LAI and dry mater production (Table 6) (37). This was favoured by higher nutrient uptake *viz.,* N (by 34.95 % and 36.17 %), P (21.35 % and 33.37 %), K (34.60 % and 33.08 %) and Zn (52.80 % and 51.57 %) over 250 kg N from urea possibly due to higher nutrient availability (Table 5). In this line, a previous study opined reported that press mud application linearly increased the NPK uptake of maize, supporting the positive effect of press mud on plant nutrition and growth (38). The combined application of NPK + press mud at 4 % significantly increased the grain and stover yield up to 11.5 % and 19.7 %, respectively in maize (39). The significant mobilization of photosynthates towards reproductive structures favoured by zinc might have increased the yield attributes and yield (40). Moreover, the application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha possibly restricted the volatilization losses and long-term supply of nutrients at critical periods, depicting higher nutrient use efficiency (41). Further, higher nitrogen fertilizer equivalence value and graded mineralization of N from press mud resulted in the highest agronomic efficiency and apparent N recovery (42). Likewise, higher partial factor productivity was achieved with the lowest quantity of nitrogen as the split application (43). However, the lowest growth and yield were recorded with 250 kg N application from urea (M_1).

Among the weed management strategies, hand hoeing at 15 and 30 DAS (S_2) led to a 77.02 – 79.70% increase in grain yield and a 70.13 – 68.53% increase in stover yield compared to unweeded control (S1) at 15 DAS. This was due to the reduced weed competition caused by lower total weed density and total weed dry weight with the highest weed control efficiency (86.15 % and 89.14 %) and weed control index (86.09 and 89.49 %) as indicated by the correlation plot of PCA (Table 4 and Fig. 3a). Additionally, hand hoeing improved soil aeration and structure, promoting root development and nutrient uptake. The resulting enhancement in photosynthates translocation from source to sink contributed to higher biomass production and yield (44, 45). Similarly, the previous study in maize revealed that hand hoeing at 15 and 30 DAS registered the lowest weed biomass, with increased weed control efficiency and uptake of nutrients by crop (46). Further, the improved weed control enhances crop nutrient uptake due to less interference with root development, enabling them to establish more extensive root systems that can explore a larger soil volume for nutrients (13, 15). It also minimizes nitrogen loss and allelopathic effects, ensuring nutrient use efficiency and crop productivity (14). However, in our study, it was on par with PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS) (S_5). It might be due to the suppressed weed density by atrazine, which resulted in a weed-free environment,


(a) Scree plot
Percentage of explained variances
100
75
50
25
0
81.5%
7%
4.5%
2%
1.9%
1.1%
0.9%
0.6%
0.3%
0%
1
2
3
4
5
6
7
8
9
10
Dimensions


(b) Correlation Plot of variables VS PCs
Dim.1
Dim.2
Dim.3
Dim.4
Dim.5
Dim.6
Dim.7
Dim.8
LAI
NU
PU
KU
ZnU
TEI
CRI
WCE
WCI
GY
SY
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

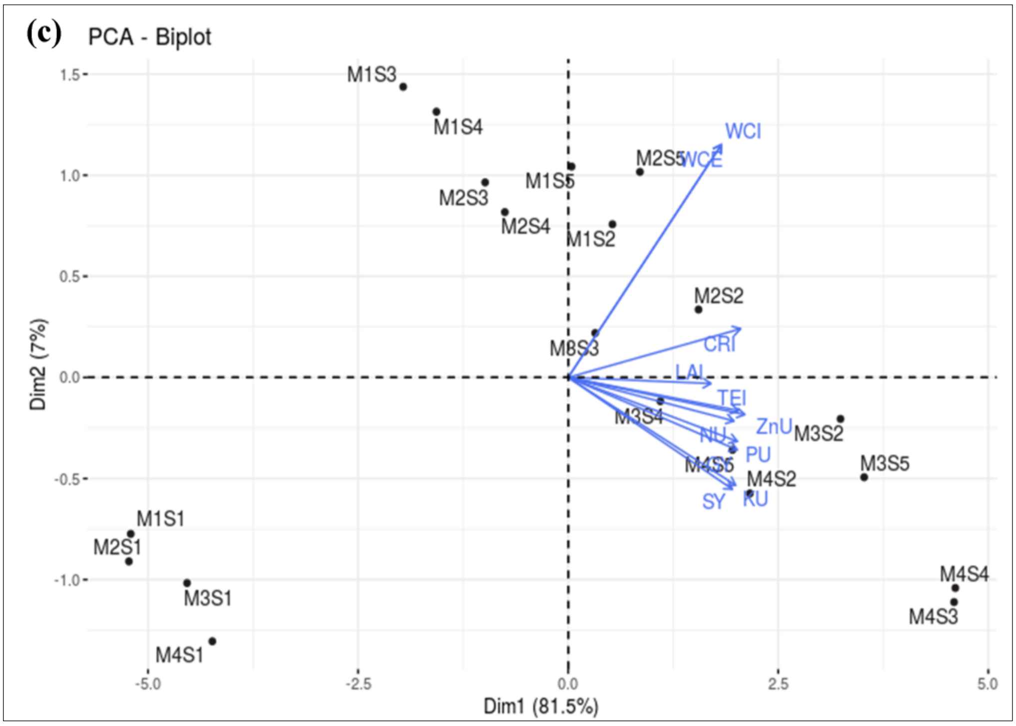


Fig. 3. The Principal Component Analysis (PCA) for the association of weed indices, maize yield and nutrient uptake due to integrated weed and nutrient management strategies. (a) Scree plot depicting the percentage of variance pertained for various parameters; 1 to 10 numbers indicate the components, (b) Correlation plot between variables and principal components and (C) Biplot depicting the interrelationship between different parameters and treatments in maize. Where, LAI – Leaf area index, NU – Nitrogen uptake, PU – Phosphorus uptake, KU - Potassium uptake, GY – Grain yield, SY - Stover yield, WCI – Weed control index, WCE – Weed control efficiency, WPI – Weed persistence index, CRI – Crop resistance index and TEI – Treatment efficiency index. M1: 250 kg N from urea, M2: M1 + 37.5 kg $ZnSO_4$, M3: 187.5 kg N from urea + 62.5 kg N from FYM + 37.5 kg $ZnSO_4$, M4: 187.5 kg N from urea + 62.5 kg N from press mud + 37.5 kg $ZnSO_4$, S1: Unweeded control, S2: Hand hoeing at 15 and 30 DAS, S3: Pre-emergence (PE) atrazine (1.0 kg a.i./ha at 3 DAS) + one hand hoeing at 30 DAS, S4: Post-emergence (PoE) topramezone (25.2 g a.i./ha at 18 DAS) + one hand hoeing at 30 DAS and S5: PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS).

avoided the crop weed competition during early crop growth stages and depicted higher nutrient availability to the crop. This resulted in higher uptake of N (by 68.7 % and 68.10 %), P (40.13 % and 48.91 %), K (47.93 % and 47.98 %) and Zn (94.28 % and 92.10 %) over control (Table 5), which was also indicated by lower post-harvest available nutrient status (Fig. 1a-d). Thus, it improved the maize growth ascribed regarding plant height, leaf area index and dry matter production. Similarly, a study reported that PE atrazine 50 % WP at 0.5 kg a.i./ha followed by PoE tembotrione 420 SC at 122 g a.i./ha at 20 DAS increased plant height, LAI and dry matter production by 104.5 %, 80.83 % and 94.69 % respectively in maize (20). Increased yield under ideal weed management strategies and higher nitrogen utilization by crop resulted in maximum nutrient use efficiencies like agronomic efficiency, apparent N recovery and partial factor productivity (Table 5). Similarly, the highest agronomic efficiency and apparent nitrogen recovery were recorded with two-hand hoeing 2 and 5 weeks after emergence in wheat (47). Meanwhile, the lowest growth and yield recorded under unweeded control (S_1) might be attributed to poor weed management strategies, which result in crop-sector competition for nutrient uptake. This favoured higher nutrient uptake by weeds rather than maize, which suppressed the vegetative growth and yield of maize with lower nutrient use efficiencies.

The interaction effect of application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha and hand hoeing at 15 and 30 DAS (M_4S_2) increased maize grain by 120 % and 125 % and stover yield by 108 % and 103 % as compared to application of 250 kg N from urea + unweeded control (M_1S_1) (Table S3). However, it was on par with application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha and PE atrazine (1.0 kg a.i./ha at 3 DAS) + PoE topramezone (25.2 g a.i./ha at 18 DAS) (M_1S_5). This was significantly associated with the combined effect of inorganic fertilizers and press mud with weed management strategies. It could result from plants receiving enough nutrients during their early growth, vital in stimulating vegetative development and increasing the sink size in flowering and seed setting (48). This was favoured by weed-free conditions with lower weed density and higher weed control efficiency during the critical period of crop weed competition, achieving higher nutrient uptake by maize (Table S1 and S2). It might have benefited the accumulation of dry matter and yield with greater treatment efficiency index (7.74 and 10.91) and crop resistance index (14.94 and 20.94), as highlighted by the biplot of PCA (Fig. 3c). Furthermore. However, the highest gross returns (Rs. 143140/ha and Rs. 149780/ha) were recorded with M_4S_2, the highest net returns (Rs. 85877/ha and Rs. 91897/ha) and benefit-cost ratio (2.54 and 2.64) were recorded with M_4S_5 due to the reduction in cost of cultivation favoured by reduction labour requirement with herbicides application (Fig. 2a-d). Hence, the superior performance was noticed with an integrated approach of application of 187.5 kg N from urea + 62.5 kg N from press mud + $ZnSO_4$ at 37.5 kg/ha and hand hoeing at 15 and 30 DAS, both in terms of yield and profitability.

Conclusion

The herbicides used in weed control have significant environmental and ecological impacts, such as reduced soil microbial diversity and abundance, affecting soil pH and nutrient transformation processes. The integrated use of herbicides, organic manures and fertilizers could curtail these adverse effects and improve maize yield. Our findings demonstrated that supplementing 62.5 kg N from press mud with 187.5 kg N from urea and hand hoeing at 15 and 30 DAS significantly increased maize grain yield in both years. However, the pre-emergence application of atrazine (1.0 kg a.i./ha at 3 DAS) followed by post-emergence topramezone (25.2 g a.i./ha at 18 DAS) was comparable to hand hoeing in terms of weed control and yield improvement. This effect was attributed to nutrient availability resulting from timely weed management through hand hoeing or herbicide application. Hence, the use of pre (atrazine) and post (topramezone) emergence herbicides in sequence, together with basal application of organic manure (press mud), reduced the labour costs, making them a viable alternative to the farmers for enhancing the productivity of maize.

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Authors' contributions

SE participated in the study's design, supervised the whole research and helped compile the manuscript. BMR carried out the field experiment and collected and analyzed data. SRV and SKN participated in data collection, compiling and analysis. SRRR and SJP validated, reviewed and edited the manuscript. ES analyzed the data and edited and drafted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no competing interests.

Ethical issues: None

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