



RESEARCH ARTICLE

Impact of sowing techniques and herbicidal interventions on weed management and residue dynamics in fodder maize

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Abstract

Fodder maize is a major fodder crop valued for its rapid growth, high biomass and superior digestibility. However, its productivity is constrained by intense weed competition and herbicide residue concerns. A field experiment was conducted during the year 2023–24 cropping season at Tamil Nadu Agricultural University, Coimbatore, in a split-plot design with two sowing methods (manual and machine sowing) and 5 weed management practices (atrazine 50 % wettable powder (WP) at 0.5 kg a.i. ha⁻¹ pre-emergence (PE) at 3 days after sowing (DAS) + hand weeding (20 DAS), topramezone at 25 g ha⁻¹ early post-emergence (EPoE) at 15 DAS, tembotrione at 0.120 kg ha⁻¹ (EPoE) at 15 DAS, mechanical weeding at 15 and 30 DAS and unweeded control). Sowing methods had no significant influence on yield or weed dynamics, though manual sowing reduced early weed biomass and machine sowing improved weed control efficiency at later stages. Among weed management practices, tembotrione recorded the highest plant growth, maximum green fodder yield (61.1 t ha⁻¹), net income (₹77648 ha⁻¹) and B:C ratio (2.79). Topramezone was most effective against broad-leaved weeds, while atrazine + hand weeding effectively managed sedges. Residue analysis showed only trace herbicide levels, all within permissible limits. Correlation and regression analyses confirmed significant positive relationships between growth traits and weed control efficiency with yield, while weed density and biomass were negatively associated with fodder yield.

Keywords: fodder maize; herbicide residue; tembotrione; weed dynamics; weed management

Introduction

Fodder maize (*Zea mays* L.) is a highly versatile crop grown for both grain and forage and in many regions, it is considered the most important cultivated fodder due to its rapid growth, high biomass production and superior digestibility (1). A consistent supply of quality green fodder is essential to sustain the expanding livestock sector and meet the rising demand for milk and meat (2). However, India faces significant deficits in livestock feed resources, with shortages of 11.24 % in green fodder, 23.4 % in dry fodder and 29 % in concentrates, while only 8.4 million hectares, approximately 4 % of the gross cropped area, are devoted to fodder production (3). Limited land availability, competition from food and cash crops and the low nutritive value of crop residues and natural pastures further constrain livestock productivity (4).

Weeds are a major constraint to fodder maize production because of their rapid germination, vigorous growth and competitive ability (5). They not only reduce yield but also decrease fodder palatability and digestibility and, in some cases, introduce

toxic or anti-nutritional compounds harmful to livestock. For instance, the presence of toxic weeds such as *Datura stramonium* L. in fodder fields may lead to poisoning in livestock when consumed with contaminated fodder (6). Reported yield losses due to weeds range from 20 % to more than 50 %, depending on the crop, weed flora and management practices (7). Manual and mechanical weeding after sowing are labour-intensive, time-consuming and less effective under heavy weed pressure, particularly during the monsoon when labour is scarce (8). Herbicides have therefore become an integral component of fodder production systems because of their broad-spectrum activity, rapid action and cost-effectiveness (9). However, extensive use of herbicides raises concerns about their persistence in soil and plant tissues and residues exceeding permissible limits may threaten livestock and human health (10–12).

Sowing methods also influence crop-weed interactions. Manual sowing often results in irregular plant stands and patchy germination, creating favourable conditions for weed growth, whereas mechanical sowing ensures uniform seed placement,

optimal plant population and rapid canopy closure, which suppresses weeds through shading and competition, while also improving input-use efficiency (13–15). Despite these advances, research combining herbicide efficacy, residue behavior and sowing methods is limited. Therefore, this study was conducted to evaluate the comparative efficiency of different herbicides on weed management, crop growth, economics and residue dynamics under manual and mechanical sowing of fodder maize.

Materials and Methods

The field experiment was conducted during the kharif (June–August 2024), rabi (September–November 2023 and 2024) and summer (March–May 2024) seasons of 2023–24 (4 crops) at the Eastern Block Farm, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore at 11° N latitude and 77° E longitude. The experimental soil was alkaline in reaction (pH 8.21), low in organic carbon (0.42 %) and available nitrogen (228 kg ha⁻¹), medium in available phosphorus (18 kg ha⁻¹) and high in available potassium (520 kg ha⁻¹). While the weather conditions during the growing season are outlined in Fig. 1.

Treatment details

The experiment was designed in a split-plot design with 3 replications. The main plot treatments comprised 2 sowing methods: M₁ - manual sowing and M₂ - machine sowing. The sub-plot treatments consisted of 5 weed management practices: S₁ - Atrazine 50 % WP at 0.5 kg a.i. ha⁻¹ as pre-emergence (PE) at 3 days after sowing (DAS) followed by hand weeding (HW) at 20 DAS; S₂ - Topramezone at 25 g ha⁻¹ as early post-emergence (PoE) at 15 DAS; S₃ - Tembotrione at 0.120 kg ha⁻¹ as early PoE at 15 DAS; S₄ - mechanical weeding twice at 15 and 30 DAS; and S₅ - unweeded control. The fodder maize variety African tall was sown at 30 cm row spacing with a seed rate of 40 kg ha⁻¹. For machine sowing, a Happy Seeder was utilised.

Assessment of growth parameters

Plant population was recorded at 15 DAS by counting plants in the net plot area and expressed as plants per square metre. At harvest, plant height was measured from ground level to the tip of the tallest fully expanded leaf on 5 randomly tagged plants and expressed in centimetre. The number of functional green leaves per plant was also recorded from these tagged plants and averaged. Stem diameter was measured at the midpoint of the stem using a measuring tape at harvest stage of the crop.

Assessment of weed parameters

Weed population was assessed at 30 and 45 DAS using a 1 × 1 m quadrat placed randomly in the net plot. All weeds within the quadrat were uprooted and oven dried at 60 °C for 48 hr after initial sun-drying until constant weight was obtained. The dry biomass was recorded plot-wise and expressed as gram per square metre.

$$\text{WCE (\%)} =$$

$$\frac{\text{Dry weight of weeds in control plot} - \text{Dry weight of weeds in treated plot}}{\text{Dry weight of weeds in control plot}} \times 100$$

Assessment of green fodder yield and economics

Green fodder yield was estimated from the net plot at harvest. Weed population data were subjected to square root transformation using the formula $\sqrt{(X+0.5)}$. Weed control efficiency (WCE) was calculated following the procedure outlined previously (16). Economic analysis of treatments included calculation of cost of cultivation, gross returns, net returns and benefit-cost ratio based on input costs and output value.

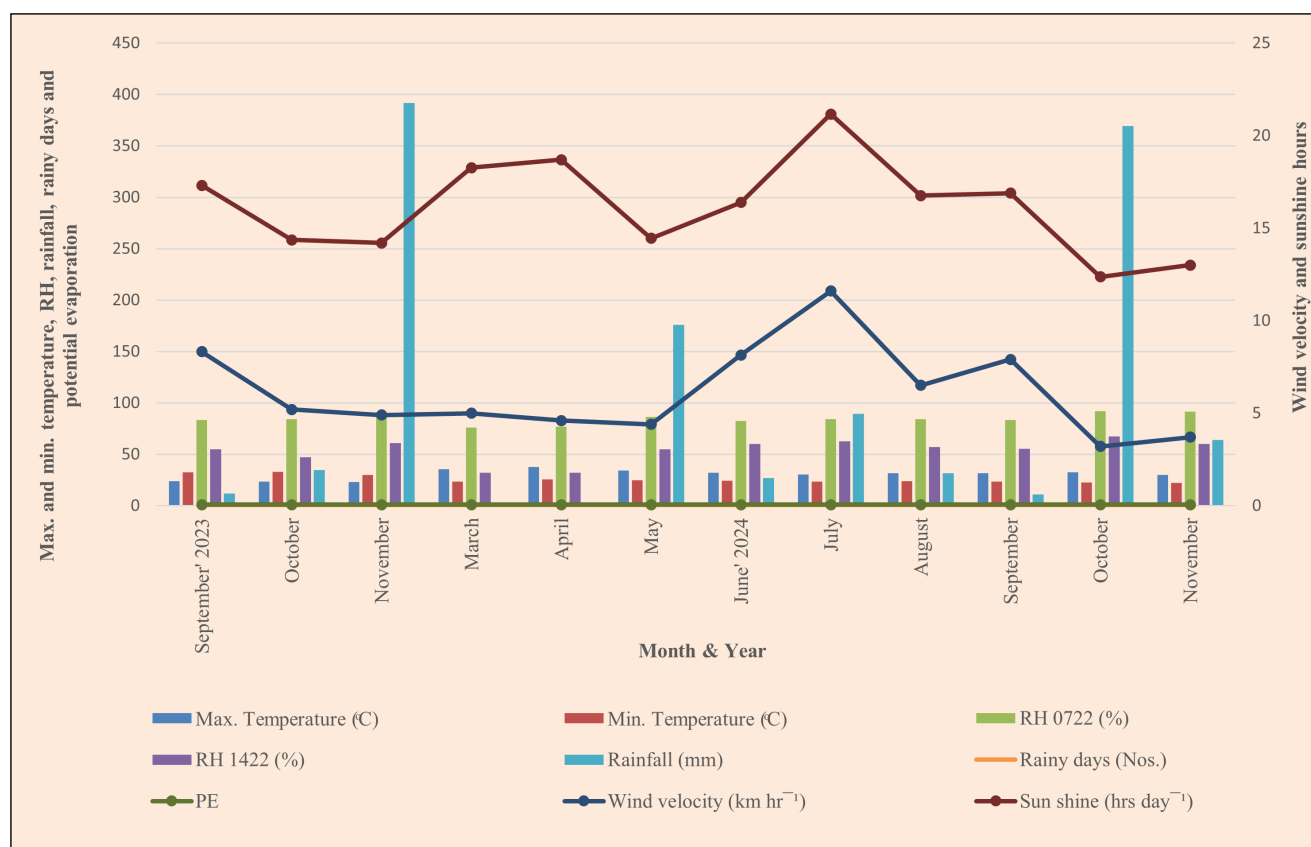


Fig. 1. Weather conditions during the growing season (2023–24).

Assessment of herbicide residue

Herbicide residues in fodder maize leaf samples were determined (17). Commonly known as the QuEChERS (Quick, Easy, Cheap, Effective, Rugged and Safe) method. Extraction step: Samples are extracted using acetonitrile containing 1 % acetic acid. The addition of anhydrous magnesium sulfate and sodium acetate induces phase separation (salting out) to move the pesticides into the organic layer. Cleanup step: A portion of the extract undergoes dispersive solid-phase extraction (d-SPE) using a combination of (to remove water) and primary secondary amine (PSA) sorbent (to remove organic acids and sugars). Analysis: The final extracts are typically analysed using liquid chromatography-tandem mass spectrometry (LC-MS/MS), which is the preferred technique for non-volatile or thermally unstable herbicides like topramezone and tembotrione. Chromatographic (LC) conditions: For multi-residue analysis of polar herbicides like topramezone alongside atrazine, an HSS T3 or C18 column is typically used to ensure sharp peak shapes and adequate retention. Column: ACQUITY UPLC HSS T3 or Zorbax Eclipse XDB-C18. Mobile phase A: Water + 0.05 % formic acid + 4 mM ammonium acetate. Mobile phase B: Acetonitrile (MeCN) + 0.1 % formic acid. Flow rate: Approximately 0.3–0.4 mL min⁻¹. Column temperature: Maintained at 35–45 °C. Gradient program: Typically starts with a high aqueous phase (e.g., 95 % A) and transitions to a high organic phase (e.g., 95 % B) over 5–15 min to elute both polar and non-polar residues. Mass spectrometry (MS/MS) parameters: The mass spectrometer operates in multiple reaction monitoring (MRM) mode. Each compound is identified by its precursor ion and at least two product ions (one for quantification, one for confirmation).

Statistical analysis

All experimental data were statistically analysed using the f-test and treatment differences were tested for significance at the 5 % probability level using critical difference (CD) values (16).

Results and Discussion

Weed density

Table 1. Grasses, sedges and broad-leaved weed (BLW) weed density (No. m⁻²) and weed dry weight (g m⁻²) as influenced by sowing and weed management methods at 30 and 45 of DAS (Pooled data 4 crops)

Treatments	Weed density (No. m ⁻²) at 30 DAS						Weed density (No. m ⁻²) at 45 DAS					
	Grasses		Sedges		BLW		Grasses		Sedges		BLW	
Sowing methods												
M ₁	3.16 (9.47)		3.98 (15.30)		5.65 (35.87)		3.15 (9.43)		3.29 (11.90)		5.53 (36.98)	
M ₂	3.26 (10.64)		3.64 (15.45)		5.94 (41.51)		3.24 (10.49)		3.41 (12.28)		5.82 (39.83)	
SEd	0.07		0.07		0.19		0.22		0.27		0.35	
CD (<i>p</i> = 0.05)	NS		0.16		NS		NS		NS		NS	
Weed management												
S ₁	2.61 (6.30)		3.09 (9.03)		4.55 (20.19)		2.23 (4.73)		2.32 (4.86)		4.48 (19.55)	
S ₂	2.29 (4.72)		2.94 (8.14)		3.38 (11.19)		2.11 (4.24)		2.62 (6.50)		3.40 (11.02)	
S ₃	2.14 (4.07)		2.84 (7.67)		4.24 (17.79)		2.04 (3.91)		2.36 (5.08)		3.44 (11.35)	
S ₄	3.16 (13.32)		4.53 (20.01)		7.21 (51.73)		3.34 (10.94)		4.46 (19.35)		6.89 (47.24)	
S ₅	4.84 (22.96)		5.70 (32.03)		9.61 (92.55)		5.00 (24.75)		5.02 (24.69)		10.17 (102.88)	
SEd	0.06		0.11		0.08		0.22		0.33		0.32	
CD (<i>p</i> = 0.05)	0.16		0.24		NS		0.48		0.69		0.67	
Interaction												
	M at S	S at M	M at S	S at M	M at S	S at M	M at S	S at M	M at S	S at M	M at S	S at M
SEd	0.10	0.07	0.13	0.12	0.08	0.06	0.21	0.18	0.40	0.42	0.38	0.52
CD (<i>p</i> = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^aValues in parenthesis () are original values; Data were square root transformed $\sqrt{X+0.5}$; BLW: broad leaved weed.

The data on weed density at 30 DAS are presented in Table 1. The predominant weed flora of the experimental site included grasses, sedges and broad-leaved species. Major weed species associated with fodder maize crop were *Digera arvensis* Fross K., *Parthenium hysterophorus* L., *Trianthema portulacastrum* L., *Sida acuta* Burm. F. among broad leaved weed (BLW); *Cynodon dactylon* (L.) Pers., *Dactyloctenium aegyptium* (L.) Wild., *Dinebra retroflexa* (Vahl.) Panzer., *Echinochloa colona* (L.) Link. among grasses and *Cyperus rotundus* L. in sedges. The interaction between sowing methods and weed control practices did not significantly influence weed density at either 30 or 45 DAS. The densities of grasses and broad-leaved weeds were not significantly affected by sowing methods at 30 DAS, since early weed emergence is largely governed by the soil seed bank and initial field conditions, with the influence of sowing method becoming evident only later in the season. These observations are consistent with previous reports (18–21). In contrast, sedges showed significant variation between sowing methods. Manual sowing (M₁) recorded slightly lower sedge density (15.30 No. m⁻²) than machine sowing (M₂), which may be attributed to reduced soil disturbance and less favourable conditions for sedge emergence. Similar results were also reported (22).

At 30 DAS, all 3 weed groups were significantly influenced by weed control methods. Application of tembotrione at 0.120 kg ha⁻¹ as early PoE at 15 DAS (S₅) resulted in the lowest densities of grasses (4.07 No. m⁻²) and sedges (7.67 No. m⁻²). For broad-leaved weeds, topamezone at 25 g ha⁻¹ as early PoE at 15 DAS (S₂) proved more effective, recording the lowest density (11.19 No. m⁻²). This reflects the strong activity of topamezone on dicot species, whereas tembotrione was more effective on grasses and sedges but slightly less effective on broad-leaved weeds. These findings are in line with the results of (23–25). The unweeded control (S₅), as expected, recorded the maximum densities of grasses (22.96 No. m⁻²), sedges (32.03 No. m⁻²) and broad-leaved weeds (92.55 No. m⁻²).

At 45 DAS, weed density data (Table 1) showed no significant effect of sowing methods or their interaction with weed management practices. However, weed control methods exerted a marked influence. Tembotrione at 0.120 kg ha⁻¹ as early PoE at

15 DAS (S_3) was highly effective against grasses, recording the lowest density (3.91 No. m^{-2}). This effectiveness is attributed to inhibition of the 4-Hydroxyphenylpyruvate dioxygenase (HPPD) enzyme essential for chlorophyll and carotenoid synthesis in grass weeds, with early application targeting them at their most susceptible stage. These results are comparable with the findings of (26–28). For sedges, atrazine 50 % WP at 0.5 kg a.i. ha^{-1} as PE at 3 DAS followed by hand weeding at 20 DAS (S_1) recorded the lowest density (4.86 No. m^{-2}), owing to the pre-emergence action of atrazine combined with manual removal of later-emerging sedges. Similar efficacy of this combination has been previously reported (24). Topramezone at 25 g ha^{-1} as early PoE at 15 DAS (S_2) was most effective against broad-leaved weeds, recording the lowest density (11.02 No. m^{-2}), which aligns with earlier findings (25, 26). On the other hand, the unweeded control (S_5) recorded the maximum densities of grasses (24.75 No. m^{-2}), sedges (24.69 No. m^{-2}) and broad-leaved weeds (102.88 No. m^{-2}).

Total weed density

The data on total weed density at 30 and 45 DAS are presented in Table 2. At both stages, sowing methods and their interaction with weed management practices did not exert any significant effect on total weed density. However, significant differences were observed among weed control methods. Application of topramezone at 25 g ha^{-1} as early PoE at 15 DAS (S_2) recorded the lowest total weed density, with 24.04 No. m^{-2} at 30 DAS and 20.34 No. m^{-2} at 45 DAS. The effectiveness of topramezone is due to inhibition of the HPPD enzyme, which blocks carotenoid biosynthesis and causes bleaching and subsequent death in both grass and broad-leaved weeds. Early post-emergence application at 15 DAS ensures that weeds are controlled at the seedling stage, preventing early competition with maize and resulting in consistently lower densities across both stages. Similar results were also reported (22, 28). In contrast, the unweeded control (S_5) registered the maximum total weed density of 147.54 No. m^{-2} at 30 DAS and 152.32 No. m^{-2} at 45 DAS.

Total weed dry weight

The data on total weed dry weight at 30 and 45 DAS are presented in

Table 2. At both stages, the interaction between sowing methods and weed management practices did not show any significant effect. However, sowing methods differed significantly at 30 DAS, while no such differences were observed at 45 DAS. Among the sowing methods, manual sowing (M_1) recorded lower total weed dry weight (14.13 g m^{-2}) compared to machine sowing (M_2). This reduction may be attributed to more uniform seed placement and better soil coverage under manual sowing, which facilitated rapid and uniform crop emergence. Consequently, the maize crop developed a denser canopy early in the season, resulting in quicker canopy closure that shaded the soil surface and suppressed weed germination and growth. Thus, weed dry weight was significantly lower under manual sowing at 30 DAS, which agrees with earlier findings (29).

Regarding weed control methods, significant differences were evident at both 30 and 45 DAS. Application of topramezone at 25 g ha^{-1} as early PoE at 15 DAS (S_2) recorded the lowest total weed dry weight, with 7.17 g m^{-2} at 30 DAS and 14.96 g m^{-2} at 45 DAS. The effectiveness of topramezone lies in its early post-emergence application, which targets weeds at the seedling stage when they are most vulnerable. As a result, weed establishment was effectively suppressed, leading to consistently lower weed dry weights at both stages. These results are in line with the previous findings (26).

Weed control efficiency

The data on WCE at 30 DAS are presented in Table 2. At 30 DAS, manual sowing (M_1) recorded higher WCE (63.33 %) compared to machine sowing (M_2). In contrast, at 45 DAS, machine sowing achieved higher WCE (70.59 %) than manual sowing. The better early performance of manual sowing may be due to closer plant spacing, which provided effective early weed suppression, whereas the uniform crop rows established through machine sowing offered stronger weed control at later stages (30).

Among the weed control methods, application of topramezone at 25 g ha^{-1} as early PoE at 15 DAS (S_2) achieved the highest WCE, recording 75.61 % at 30 DAS and 78.39 % at 45 DAS. This may be attributed to effective control of emerging weeds during

Table 2. Total weed dry weight (g m^{-2}) and weed control efficiency (WCE) as influenced by sowing methods and weed management methods at 30 and 45 DAS

Treatments	Total weed density (No. m^{-2})		Total weed dry weight (g m^{-2})		WCE	
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS
Sowing methods						
M_1	7.89 (60.26)	7.66 (58.32)	3.76 (14.13)	5.25 (27.59)	63.33	67.98
M_2	8.29 (68.08)	8.40 (70.14)	3.90 (15.22)	5.49 (30.10)	62.49	70.59
SEd	0.19	0.28	0.07	0.19	-	-
CD ($p = 0.05$)	NS	NS	0.16	NS	-	-
Weed management						
S_1	6.00 (35.51)	5.45 (29.14)	2.85 (8.15)	4.15 (17.19)	73.43	74.70
S_2	4.95 (24.04)	4.57 (20.34)	2.68 (7.17)	3.87 (14.96)	75.61	78.39
S_3	5.48 (29.53)	4.71 (21.75)	2.72 (7.38)	3.97 (15.80)	74.80	77.00
S_4	9.20 (84.25)	8.83 (77.52)	4.61 (21.28)	5.82 (33.91)	27.83	47.06
S_5	12.16 (147.54)	12.36 (152.32)	5.42 (29.40)	6.65 (44.17)	-	-
SEd	0.25	0.33	0.12	0.21	-	-
CD ($p = 0.05$)	0.56	1.05	0.26	0.47	-	-
Interaction						
SEd	M at S S at M	M at S S at M	M at S S at M	M at S S at M	M at S S at M	M at S S at M
CD ($p = 0.05$)	0.40 0.40	0.30 0.27	0.11 0.13	0.40 0.43	- -	- -
	NS NS	NS NS	NS NS	NS NS	NS NS	NS NS

Values in parenthesis () are original values; Data were square root transformed $\sqrt{X+0.5}$; WCE: weed control efficiency; DAS: days after sowing.

Table 3. Growth parameters and green fodder yield of fodder maize as influenced by sowing and weed management methods

	Growth parameters						Yield			
Treatments	Plant population at 15 DAS (No. m ⁻²)		No. of leaves plant ⁻¹		Stem girth (cm)		Plant height (cm)		Green fodder yield (t ha ⁻¹)	
Sowing methods										
M ₁	21.8		13.0		1.64		278.3		52.1	
M ₂	21.3		13.0		1.63		276.2		51.3	
SEd	0.7		0.4		0.05		8.8		1.7	
CD (<i>p</i> = 0.05)	NS		NS		NS		NS		NS	
Weed management										
S ₁	21.8		13.4		1.65		297.9		60.1	
S ₂	22.2		13.4		1.67		299.1		61.0	
S ₃	22.2		13.6		1.68		299.7		61.1	
S ₄	21.2		12.3		1.64		259.6		43.2	
S ₅	20.5		12.4		1.54		229.6		31.3	
SEd	0.8		0.8		0.03		9.2		1.6	
CD (<i>p</i> = 0.05)	NS		NS		0.08		19.4		3.6	
Interaction	M at S	S at M	M at S	S at M	M at S	S at M	M at S	S at M	M at S	S at M
SEd	1.9	1.8	1.2	1.8	0.03	0.03	10.4	11.6	3.5	3.6
CD (<i>p</i> = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

the critical crop growth stage, which reduced weed competition and maintained higher WCE at both observation periods. These findings are in accordance with earlier results (26).

Growth and green fodder yield of fodder maize

The growth parameters and green fodder yield of fodder maize are presented in Table 3. The results revealed that both sowing methods and weed control practices influenced crop growth and fodder yield. However, sowing methods and their interaction with weed control practices did not show a significant effect, as crop performance is largely determined by nutrient management and variety selection (31, 32).

Among the weed management practices, significant differences were observed in stem girth, plant height and green fodder yield. Plant population remained unaffected by sowing methods, weed control practices, or their interaction. Application of tembotrione 0.120 kg ha⁻¹ as early PoE at 15 DAS (S₃) recorded the highest growth, including number of leaves per plant (13.6), stem girth (1.68 cm), plant height (299.7 cm) and green fodder yield (61.1 t ha⁻¹) compared to the unweeded control (S₅). The superior performance under tembotrione is attributed to effective weed suppression, which allows maize plants better access to nutrients, water and light. This promotes stronger physiological development, including more leaves, thicker stems and greater height, ultimately leading to higher fodder yield, consistent with earlier findings (33).

Economics

The economics of fodder maize cultivation are presented in Table 4. Higher crop productivity with lower cultivation costs contributed to improved economic returns, including gross returns, net returns and B:C ratio. Among sowing methods, machine sowing (M₂) recorded lower cultivation costs (₹40967 ha⁻¹), higher net returns (₹62113 ha⁻¹)

and a higher B:C ratio (2.51) compared to manual sowing (M₁). This is due to reduced labor requirements, better crop establishment and more efficient resource use, which together enhanced overall profitability (34).

Among weed management practices, the highest cost of cultivation (₹52512 ha⁻¹) was recorded under Atrazine 50 % WP at 0.5 kg a.i. ha⁻¹ as PE at 3 DAS followed by hand weeding at 20 DAS (S₁). The higher cost is due to combined expenses for chemical input and manual labour, as also reported (35). In contrast, application of tembotrione 0.120 kg ha⁻¹ as early PoE at 15 DAS (S₃) resulted in the highest gross returns (₹122200 ha⁻¹), net returns (₹77648 ha⁻¹) and B:C ratio (2.79). Effective weed control under tembotrione promoted robust maize growth, resulting in higher green fodder yield and improved economic performance, consistent with earlier study (36).

Herbicide residue in green fodder of maize

Topramezone, tembotrione and atrazine residues were detected in the green fodder of maize at 60 days after herbicide application i.e. at harvesting stage (Table 5). Topramezone were found 0.03 mg kg⁻¹, tembotrione at 0.02 mg kg⁻¹ and atrazine at 0.01 mg kg⁻¹. Similar results were also reported (37). Maximum residue limits (MRLs) of selected herbicides in fodder maize (corn forage) given in Table 6. The limit of quantification (LOQ) of the analytical method for herbicide residues was 0.005 mg kg⁻¹ (Table 7) indicating the lowest concentration that could be quantified reliably. Since the detected residues of atrazine, tembotrione and topamezone at harvest were

Table 5. Residue content of herbicides in fodder maize at 60 DAS

Herbicides	Residue level at 60 DAS (mg kg ⁻¹)
Atrazine	0.01
Tembotrione	0.02
Topramezone	0.03

Table 4. Economics of fodder maize as influenced by sowing and weed management methods

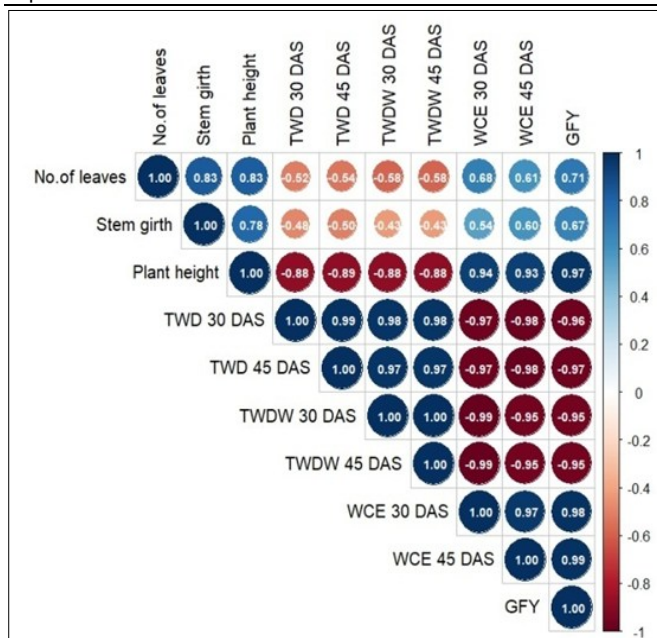
Treatments	Economics			
	Cost of cultivation (₹ ha ⁻¹)	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	B:C ratio
Sowing methods				
M ₁	52127	104120	51993	1.99
M ₂	40967	103080	62113	2.51
Weed management				
S ₁	52512	120800	68288	2.33
S ₂	44648	121500	76852	2.76
S ₃	44552	122200	77648	2.79
S ₄	50912	92700	41788	1.84
S ₅	40112	60800	20688	1.55

Table 6. Maximum residue limits (MRLs) of selected herbicides in fodder maize (corn forage)

Herbicide	Commodity (equivalent to fodder maize)	MRL (mg kg ⁻¹)	Regulatory agency
Atrazine	Corn field forage	1.5	United States Environmental Protection Agency (2003)
Tembotrione	Corn field forage	0.60	United States Environmental Protection Agency (2007)
Topramezone	Corn field forage	0.05	United States Environmental Protection Agency (2010)

Table 7. Limit of quantification of herbicides

Herbicides	Limit of quantification (mg kg ⁻¹)
Atrazine	0.005
Tembotrione	0.005
Topramezone	0.005

**Fig. 2.** Correlation between weed parameters, growth characters and yield attributes of fodder maize.

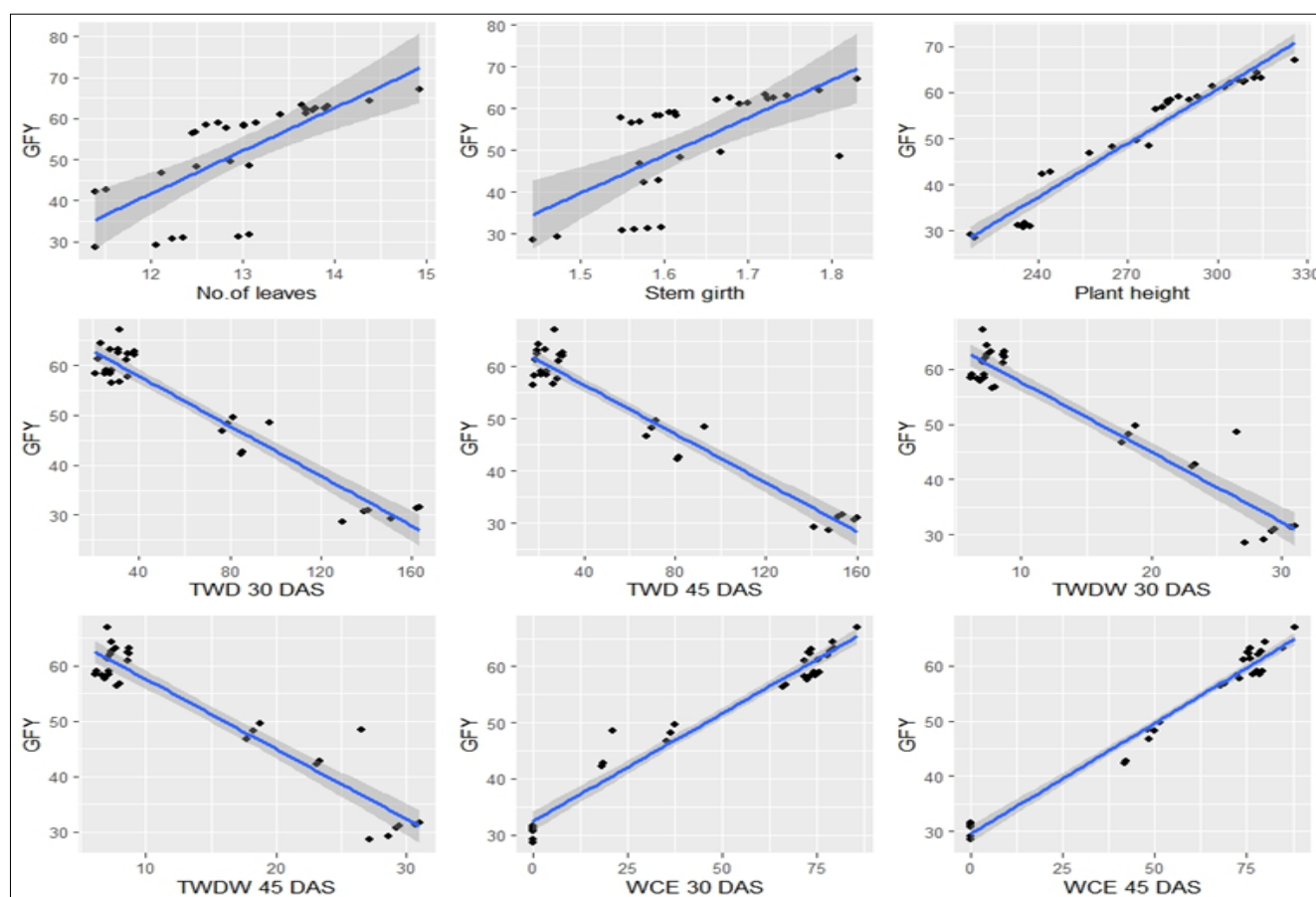
above the LOQ, the quantified values presented in Table 5 were considered accurate and within the detectable range of the method.

Correlation analysis

The correlation analysis revealed that all the studied variables exhibited significant associations with green fodder yield (GFY) (Fig. 2). Growth parameters such as number of leaves, stem girth and plant height showed strong positive correlations with GFY ($r = 0.67$ – 0.97), confirming that vegetative vigour directly enhanced fodder productivity. Among these, plant height recorded the highest positive correlation with GFY ($r = 0.97$). In contrast, total weed density (TWD) and total weed dry weight (TWDW) measured at 30 and 45 DAS were highly and negatively correlated with GFY ($r = -0.95$ to -0.97), highlighting the suppressive role of weed interference on crop growth and yield. Weed control efficiency (WCE) at 30 and 45 DAS exhibited a very strong positive correlation with GFY ($r = 0.98$ – 0.99), suggesting that efficient weed suppression substantially contributed to yield enhancement. These findings indicate that both crop growth traits and weed management indices are crucial determinants of fodder yield performance.

Regression analysis

The regression analysis quantified the extent to which individual crop growth and weed parameters explained the variability in GFY (Fig. 3). The coefficient of determination (R^2) indicated that plant height explained the highest proportion of variation in GFY

**Fig. 3.** Multiple regression analysis to estimate the yield of fodder maize.

($R^2 \approx 0.95$), followed by number of leaves ($R^2 \approx 0.78$) and stem girth ($R^2 \approx 0.72$), demonstrating that improvements in crop structural development substantially contributed to yield formation. In contrast, weed pressure variables accounted for considerable reductions in yield, as reflected by high negative explanatory power of TWD at 30 and 45 DAS ($R^2 \approx 0.88$ and 0.90) and TWDW at 30 and 45 DAS ($R^2 \approx 0.92$ and 0.94), indicating that increased weed proliferation strongly constrained fodder productivity. Conversely, WCE emerged as a major positive determinant of yield, with WCE at 30 and 45 DAS explaining a large proportion of yield variation ($R^2 \approx 0.96$ and 0.97). Overall, the regression models demonstrate that variability in GFY is largely governed by crop growth vigour and the degree of weed suppression achieved during the critical crop growth stages.

Conclusion

The study demonstrated that effective weed management and appropriate sowing methods are vital for achieving higher productivity and profitability in fodder maize. Among the treatments, early post-emergence application of tembotrione at 0.120 kg ha^{-1} at 15 days after sowing (DAS) significantly reduced weed density and biomass, enhanced weed control efficiency (WCE) and produced the highest green fodder yield and net returns. Machine sowing proved economically superior due to reduced labour costs and efficient crop establishment. Herbicide residues in green fodder were well below permissible limits, ensuring fodder safety. Correlation and regression analyses revealed that crop growth traits and weed suppression are strongly and positively associated with green fodder yield (GFY), suggesting that a balanced integration of chemical and agronomic practices can enhance weed management efficiency and support sustainable fodder maize productivity.

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Authors' contributions

SPS wrote the manuscript draft and KT revised it. VM, GP, SV, NS, RJ and MV verified contents. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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