PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-9
https://doi.org/10.14719/pst.7353

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RESEARCH ARTICLE

Evaluating the impact of pre- and post-emergence herbicides on weed dynamics and sustainable Maize cultivation practices

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OPEN ACCESS

ARTICLE HISTORY
Received: 21 January 2025
Accepted: 15 March 2025
Available online
Version 1.0 : 28 March 2025
Version 2.0 : 01 April 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

CITE THIS ARTICLE
Anand G, Arshdeep S, Kritika, Guttikonda PS, Zeeshan AS, Shimpy S, Sanchit T, Iza F. Evaluating the impact of pre- and post-emergence herbicides on weed dynamics and sustainable Maize cultivation practices. Plant Science Today. 2025; 12(2): 1-9. https://doi.org/10.14719/pst.7353

Abstract

Weed management is essential for sustainable maize cultivation, as unchecked weed growth can substantially reduce crop yields by competing for nutrients, water and sunlight. Herbicide treatments provide a more effective alternative to labor-intensive, frequently unfeasible manual weeding techniques for large-scale operations. A field trial was conducted in Lovely Professional University, Phagwara, Punjab during the Kharif season of 2024 to evaluate several herbicide combinations on maize. The experiment followed a randomized block design containing 11 treatments and 3 replications. The predominant weed species identified throughout the study were *Eleusine indica, Digera arvensis, Cyperus rotundus, Dactyloctenium aegyptium* and *Cyperus compressus*. Hand weeding at 20 and 40 days after sowing (DAS) yielded the most effective weed control, significantly decreasing weed density and biomass. The combined application of Atrazine (1000 g ha^{-1}) and Tembotrione (120 g a.i. ha^{-1}) shown the greatest chemical control efficacy, reducing *Eleusine indica* density to 16.07 m^2, *Digera arvensis* to 19.17 m^2 and *Cyperus rotundus* to 30.02 m^2. This combination demonstrated the highest weed control efficiency (WCE), attaining 77.90 % for *Eleusine indica*, 84.10 % for *Digera arvensis* and 81.00 % for *Cyperus rotundus*. The combination of Atrazine and Tembotrione produced maximum maize growth, resulting in the tallest plants (175.8 cm), the highest leaf number (12.00 leaves plant-^{1}), the largest leaf area (458.38 cm^2) and the thickest stem diameter (7.26 cm). The chlorophyll index (SPAD) reached its highest in this treatment (44.8), indicating increased photosynthetic efficiency. Atrazine (1000 g ha^{-1}) combined with Tembotrione (120 g a.i. ha^{-1}) identified as the most effective herbicide treatment for weed suppression while enhancing maize development, providing an effective substitute for labor-intensive manual weeding.

Keywords

chemical weed control; crop-weed competition; herbicide efficacy; pendimethalin; sustainable agriculture; tembotrione ; weed management

Introduction

Zea mays L. or maize, is an important cereal crop that has considerable worldwide significance. It is a key source of feed, industrial raw materials and food. It is essential to food security because of its great adaptability to a wide range of agroclimatic conditions, particularly in emerging nations. Both rain-fed and irrigated maize is widely grown in India, where it makes a substantial contribution to the agricultural economy of the nation (1). Maize occupied 11.24 m ha area, 37.67 mt and 3351 kg ha^{-1} yield in India during 2023-24. Maize occupied 93.3 thousand hectares area, producing 410 thousand tonnes in the Punjab State during 2022-23. The average yield was 43.93 q ha^{-1} (2). Maize has been utilized more and more recently as a feedstock and to produce bioethanol. It is crucial to keep weeds, pests and diseases away from maize in order to prevent significant losses in production and quality. In most cases, weed control is the most crucial because weed interference in corn can be particularly problematic early in the growing season because of the crop's slower initial growth rate and more row spacing (3). Among the numerous biotic (insects, pests, predators and weeds) and abiotic elements (drought, salt, heat, etc.) that impede maize production, weeds are regarded as one of the primary constraints on maize crop productivity. Weeds can significantly reduce maize yield and can lead to total crop failure. The detrimental impact of weeds can be attributed to their competition with maize for light, water and nutrients, leading to diminished growth and yield of the crop. The reduction in maize production primarily results from competition with weeds. As a crop cultivated during the rainy season, it experiences significant weed infestations, resulting in substantial losses between 28 and 100 % (4). *Digera arvensis, Commelina benghalensis, Amaranthus viridis, Celosia argentea, Euphorbia hirta, Lagasca mollis and Parthenium hysterophorus* were predominant broad-leaved weeds, while *Cyperus rotundus, Cynodon dactylon* and *Dinebra arabica* were the prevalent narrow-leaved grassy weeds (5). Depending on the type of weed flora and its intensity, stage, nature and critical period of crop weed competition, yield losses resulting from weed infestation might range from 28 to 93 % (6). In maize, the important time for crop weed competition is 1st - 8th weeks after sowing. Weed infestations, on the other hand, usually pose a threat to crop productivity because they compete with crops for nutrients, water and light, resulting in lower yield and quality. During this time, weed control becomes essential to achieving maize's maximal yield potential. Managing weeds is essential to maximizing maize yield. Especially in large-scale farming operations, traditional weed management techniques like manual weeding are time-consuming, labor-intensive and frequently ineffective (7). Due to this, there is now a greater need for herbicides, which provide a more workable way to manage weeds. Herbicides are essential for reducing weed competition in the important early phases of crop development, especially when applied pre- and post-emergence. During the crucial period of crop weed competition, chemical weed management with pre- or post-emergence herbicides can result in the efficient and economical control of weeds, which may not be achieved with manual or mechanical weeding due to its high cultivation costs (8). Herbicides known as pre-emergence are sprayed on the soil before weed seeds sprout, creating a barrier that prevents weed development. Limited herbicides such as atrazine, oxyfluorfen, 2,4-D and pendimethalin are available for weed management in maize. Currently, farmers are utilizing only 2,4-D at 1.0 kg ha^{-1} or atrazine at 1.0 kg ha^{-1} as post-emergence herbicides in maize; however, these herbicides primarily target broad-leaf weeds. The management of grasses and sedges continues to provide challenges for farmers, particularly when excessive or insufficient soil moisture hinders intercultural operations and shortages of labor arise during critical weeding periods (9) Conversely, post-emergence herbicides are sprayed after the weeds have emerged and are designed to target them at particular stages of growth. Both strategies have shown success in managing a variety of weed species, but further research is needed to determine how they will affect weed dynamics and the overall sustainability of maize production methods (10). The purpose of this study was to evaluate how herbicide applications, both pre and post-emergence, affect the dynamics of weeds in maize fields. The goal of the research is to shed light on sustainable weed management strategies by assessing the effectiveness of these herbicides in managing dominant weed species and examining their impact on maize development.

Materials and Methods

Experimental site and details

Herbicidal efficacy was evaluated by applying pre-emergence and post-emergence herbicides, compared to a standard herbicide, hand weeding and a weedy control in maize cultivation during Kharif 2024 at the Agronomic Research Area of Lovely Professional University, Phagwara, Punjab. The agricultural field is in the Northern Plain zone, with coordinates at Latitude 31° N and Longitude 75° E. The farm is located 250m above sea level. The average annual precipitation received by the region is 628 mm. The average weather parameters during crop period are given in Fig. 1. The experiment was conducted using a randomized block design with a net plot size of 5 × 4 m and three replications. Total 11 treatments imposed in 3 replications used in the study mentioned in the Table 1.

Experimental materials

Maize hybrid (NK 7328) was planted at the recommended seed rate of 25 kg per hectare, with a row spacing of 60 cm. A plant-to-plant distance of 20 cm was attained by reducing excess plants during the early growth period. 120 kg of nitrogen and 60 kg of Phosphorus per hectare were treated in the form of urea and diammonium phosphate (DAP), respectively. The entire quantity of phosphorus and half of the nitrogen was applied and incorporated into the soil at sowing, while the remaining half of the nitrogen was applied as a top dressing. Pre-emergence herbicides were applied within two days after sowing. Post-emergence herbicides were used at 15-20 DAS all herbicides were applied following the preparation of a spray volume of 500 lha^{-1}. The herbicides were applied immediately following the sowing of the maize crop using a "Knapsack" hand sprayer equipped with a flat fan nozzle. The spray volume was determined via the standard calibration method. All other agronomic procedures performed uniformly and consistently throughout all treatments.

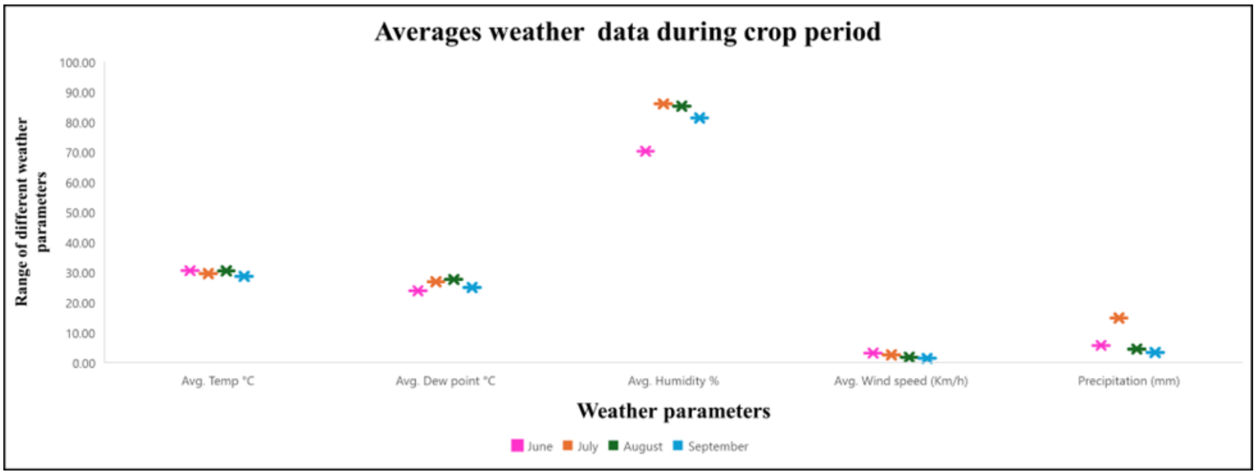

Fig. 1. Weather parameters during crop period.

Table 1. Treatment details

Treatments	Treatments detail
T_0	Weedy check
T_1	Hand weeding at (20,40 DAS)
T_2	Atrazine @1000 g ha^{-1}
T_3	Pendimethalin @1kg ha^{-1}
T_4	2,4-D amine salt 580g ha^{-1}
T_5	Tembotrione @120g a.i. ha^{-1}
T_6	Atrazine @500 g ha^{-1} + Pendimethalin 500g ha^{-1}
T_7	Atrazine @500 g ha^{-1} + 2,4-D amine salt 290g ha^{-1}
T_8	Pendimethalin 500g ha^{-1} + 2,4-D amine salt 290g ha^{-1}
T_9	Atrazine @1000 g ha^{-1} + Tembotrione @120g a.i. ha^{-1}
T_{10}	Pendimethalin @1kg ha^{-1}+ Tembotrione @120g a.i. ha^{-1}

Parameters of study and statistical analysis

Weed density was measured at 20 and 40 DAS using a $1m^2$ quadrat from the center of the field. All weeds within the quadrate were removed and cut within the center of root and shoot in each plot and subsequently gathered for dry matter accumulation (biomass). The samples were initially sun-dried and subsequently placed in an oven at 70 ± 2°C. The dried samples were measured and calculated as biomass (g m^{-2}). A square root transformation was applied to weed density and weed biomass using the formula $\sqrt{x}$ + 0.5. Weed control efficiency (WCE) was computed using the formulas (6). The data on plant height (cm), stem girth (cm), leaf area (cm^2), chlorophyll index (SPAD), crop growth rate (CGR) and relative growth rate (RGR) were statistically analyzed using Fisher's analysis of variance and the least significant difference (LSD) test at a 5 % probability level to compare significant treatment means by OPSTAT software.

Results

Weed flora

Among the weeds, grasses and sedges were dominant in the experimental site compared to the broad-leaved weeds: *Eleusine indica, Digera arvensis* were the major grassy weeds and *Cyperus rotundus* was the dominant sedge weed.

Impact of different herbicide treatments on weed density

Evaluates the effectiveness of different treatments in managing the weed species *Eleusine indica, Digera arvensis and Cyperus rotundus* at 20 and 40 Days After Sowing (DAS). The interventions consist of various herbicides utilized individually or in conjunction, in addition to manual weeding and a weedy control group. The findings offer insights into the comparative efficacy of each treatment in controlling weed infestations. The analysis is predicated on weed density (No. m^{-2}) and total weed density at 40 DAS represented in Table 2.

Eleusine indica weed density

The weedy check documented the highest density *of Eleusine indica,* with 65.29 m^{-2} at 20 DAS and 76.10 m^{-2} at 40 DAS, demonstrating the vigorous growth of this weed species in untreated plots. The overall weed density in the control group was 141.39 m^{-2}. Hand weeding at 20 and 40 DAS markedly diminished weed density, yielding one of the lowest value 13.76 m^{-2} at 20 DAS and 4.52 m^{-2} at 40 DAS, resulting in a total of 18.27 m^{-2}. This method of treatment proved exceptionally effective in controlling *Eleusine indica* but necessitates much labor. The combination of Atrazine at 1000 g ha^{-1} and Tembotrione at 120 g a.i. ha^{-1} exhibited the most significant reduction in weed density, recording 11.64 m^{-2} at 20 DAS and 4.43 m^{-2} at 40 DAS, resulting in an overall weed density of 16.07 m^{-2}. This combination was comparable to hand weeding, demonstrating its efficacy as a chemical alternative. Atrazine, a photosystem II inhibitor, disrupts photosynthesis by obstructing electron transport in photosystem II, resulting in chlorosis and mortality of weeds (7). Tembotrione inhibits the enzyme HPPD (4-hydroxyphenylpyruvate dioxygenase), hence interrupting carotenoid production, resulting in whitening and plant mortality (8). The application of 2,4-D amine salt at 580 g ha^{-1} resulted in a greater density of *Eleusine indica*, recording 26.26 m^{-2} at 20 DAS and 17.57 m^{-2} at 40 DAS, yielding the greatest total weed density of 43.83 m^{-2} among the herbicide treatments. 2,4-D amine salt was less efficacious in managing this weed. 2,4-D simulates the plant hormone auxin, resulting in unregulated growth and subsequent mortality (9). Nonetheless, its effectiveness against *Eleusine indica* is inferior to that of other herbicides.

Table 2. Effect of pre and post emergence herbicides on weed density for different species of weed

Treatments	*Eleusine indica* (No. m^{-2}) 20 DAS	*Eleusine indica* (No. m^{-2}) 40 DAS	Total weed density of *Eleusine indica* (No. m^{-2})	*Digera arvensis* (No. m^{-2}) 20 DAS	*Digera arvensis* (No. m^{-2}) 40 DAS	Total weed density of *Digera arvensis* (No. m^{-2})	*Cyperus rotundus* (No. m^{-2}) 20 DAS	*Cyperus rotundus* (No. m^{-2}) 40 DAS	Total weed density *Cyperus rotundus* (No. m^{-2})
Weedy check	8.58^{a} (65.29)	9.22^{a} (76.103)	12.39^{a} (141.39)	4.84^{a} (18.87)	5.52^{a} (25.3)	7.140^{d} (44.14)	5.76^{a} (27.64)	6.36^{a} (34.40)	34.40^{a} (62.04)
Hand weeding at (20, 40 DAS)	4.21^{fg} (13.76)	2.62^{d} (4.52)	4.773^{ef} (18.27)	3.99^{c} (12.23)	2.61^{de} (4.5)	4.580^{c} (16.71)	4.35^{d} (14.87)	2.82^{de} (5.40)	5.40^{f} (20.26)
Atrazine @1000 g ha^{-1}	4.35^{ef} (14.87)	4.11^{bc} (13.1)	5.783^{d} (27.95)	3.07^{d} (6.63)	2.84^{cd} (5.5)	3.978^{de} (12.17)	4.84^{cd} (18.86)	5.07^{c} (20.87)	20.87^{d} (39.72)
Pendimethalin @1kg ha^{-1}	4.58^{e} (16.64)	4.98^{b} (20.047)	6.556^{b} (36.68)	3.09^{d} (6.73)	2.96^{c} (6.1)	4.074^{d} (12.8)	5.20^{bc} (22.08)	5.69^{b} (26.96)	26.96^{c} (49.04)
2,4-D amine salt 580g ha^{-1}	5.62^{b} (26.26)	4.69^{b} (17.57)	7.116^{b} (43.83)	4.52^{b} (16.23)	3.87^{b} (11.4)	5.749^{b} (27.63)	4.43^{d} (15.47)	2.28^{f} (3.20)	3.20^{e} (18.67)
Tembotrione @120g a.i. ha^{-1}	4.93^{d} (19.63)	3.87^{c} (11.403)	6.068^{cd} (31.03)	4.72^{ab} (17.78)	3.24^{b} (7.6)	5.531^{b} (25.34)	4.51^{d} (16.18)	2.63^{ef} (4.57)	4.57^{e} (20.75)
Atrazine @500 g ha^{-1} + Pendimethalin 500g ha^{-1}	5.23^{b} (22.41)	4.34^{b} (14.763)	6.596^{b} (37.17)	3.11^{d} (6.83)	3.71^{b} (10.3)	4.641^{bc} (17.17)	5.35^{ab} (23.63)	6.29^{a} (33.61)	33.61^{b} (57.24)
Atrazine @500 g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	5.47^{b} (24.71)	4.06^{bc} (12.700)	6.615^{b} (37.41)	3.74^{c} (10.53)	3.43^{b} (8.6)	4.875^{b} (19.17)	5.55^{ab} (25.52)	3.03^{de} (6.40)	6.40^{e} (31.92)
Pendimethalin 500g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	5.06^{cd} (20.80)	4.12^{bc} (13.097)	6.322^{bc} (33.9)	3.96^{c} (12.00)	2.85^{cd} (5.60)	4.684^{bc} (17.57)	5.65^{ab} (26.62)	3.08^{d} (6.70)	6.70^{e} (33.32)
Atrazine @1000 g ha^{-1} + Tembotrione @120g a.i. ha^{-1}	3.91^{g} (11.64)	2.60^{d} (4.433)	4.509^{f} (16.07)	2.60^{e} (4.47)	2.27^{f} (3.1)	3.254^{f} (7.6)	5.55^{ab} (25.52)	2.61^{ef} (4.50)	5.976^{f} (30.02)
Pendimethalin @1kg ha^{-1}+ Tembotrione @120g a.i. ha^{-1}	4.32^{ef} (14.64)	2.69^{d} (4.887)	4.913^{e} (9.523)	3.05^{d} (6.53)	2.54^{ef} (4.2)	3.770^{e} (10.7)	5.32^{ab} (23.31)	2.85^{de} (5.53)	5.868^{f} (28.84)
CD(p<0.05)	0.289	0.361	0.322	0.115	0.247	0.25	0.246	0.196	0.443

*Values in parentheses are original values as observed, while without parentheses are transformed (√x+0.5) values

Digera arvensis weed density

The weedy check demonstrated the highest density of *Digera arvensis,* recording 18.87 m^{-2} at 20 DAS and 25.3 m^{-2} at 40 DAS, resulting in a total weed density of 44.14 m^{-2}. Hand weeding achieved superior control, resulting in a total weed density of 16.71 m^{-2}, markedly diminishing the infestation. Atrazine at 500 g ha^{-1} combined with 2,4-D amine salt at 290 g ha^{-1} and Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} demonstrated the most efficacious chemical control, resulting in overall weed densities of 19.17 and 10.7 m^{-2}, respectively. The application of 2,4-D amine salt at 580 g ha^{-1} resulted in a total weed density of 27.63 m^{-2} which was comparatively increased relative to other treatments, suggesting that this herbicide was also less effective against *Digera arvensis*. This result is supported by the findings of (8). Pendimethalin is a pre-emergent herbicide that hinders the development of roots and shoots by interfering with microtubule formation during cellular division. The efficacy of weed control is augmented when used in combination with Tembotrione as reported by (10) in maize crops.

Cyperus rotundus weed density

The weedy check once again exhibited the highest density of *Cyperus rotundus*, with 62.04 m^{-2}. Hand weeding resulted in a substantial decrease in weed density, reducing the total to 20.26 m^{-2} hence proving highly successful in managing *Cyperus rotundus*. Atrazine at 500 g ha^{-1} combined with Pendimethalin at 500 g ha^{-1} exhibited the most effective control, resulting in a total density of 33.61 m^{-2}, closely followed by Atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1}, which yielded 30.02 m^{-2}. Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} demonstrated efficacy, resulting in a total weed density of 28.84 m^{-2}. Nonetheless, the application of 2,4-D amine salt at 580 g ha^{-1} resulted in a greater density (18.67 m^{-2}) of *Cyperus rotundus*, signifying reduced efficacy. Atrazine at 500 g ha^{-1} mixed with Pendimethalin at 500 g ha^{-1} demonstrated effective control by inhibiting root development and photosynthesis (11).

Impact of different herbicide treatments on weed biomass and WCE %

Total weed biomass of Eleusine indica (g m^{-2}) and WCE %: The weedy check exhibited the greatest biomass of *Eleusine indica* (336.767 gm^{-2}), indicating the uncontrolled and unrestricted proliferation of this weed in the absence of management strategies. Hand weeding (20, 40 DAS) markedly diminished biomass to 83.8 g m^{-2} demonstrating the effectiveness of manual eradication in suppressing weed proliferation. This provided a WCE of 74.03 %. The combination of Atrazine at 1000 g ha^{-1} and Tembotrione at 120 g a.i. ha^{-1} proved to be the most efficacious chemical treatment, yielding a total biomass of 66.833 g m^{-2} and a weed control efficacy (WCE) of 77.90 %, indicating its effectiveness in mitigating weed proliferation. The herbicide combination's dual mechanism (photosystem II suppression by Atrazine and HPPD inhibition by Tembotrione) significantly impairs the metabolic and carotenoid production pathways in *Eleusine indica*. 2,4-D amine salt at 580 g ha^{-1} and Tembotrione at 120 g ha^{-1} shown reduced efficacy, yielding biomasses of 133.433 g m^{-2} and 126.833 gm^{-2} respectively, along with decreased WCEs of 62.34 % and 63.16 %. These herbicides are less effective for suppressing *Eleusine indica* or necessitate improved application time (12-14) for enhanced efficacy in maize as represented in Table 3.

Total weed biomass of Digera arvensis (g m^{-2}) and % : The weedy check exhibited the highest biomass of *Digera arvensis* (236.100 gm^{-2}), demonstrating its significant dominance when left uncontrolled. Hand weeding produced the minimal biomass (44.1 gm^{-2}) alongside the highest weed control efficiency (85.84 %), establishing hand

Table 3. Effect of pre and post emergence herbicides on weed biomass and weed control efficiency % for different species of weed

Treatments	Total weed biomass of *Eleusine indica* (gm^{-2})	Total weed biomass of *Digera arvensis* (gm^{-2})	Total weed biomass of *Cyperus rotundus* (gm^{-2})	WCE % *Eleusine indica*	WCE % of *Digera arvensis*	WCE % of *Cyperus rotundus*
Weedy check	18.36^{a} (336.76)	15.382^{a} (236.1)	14.53^{a} (210.9)	-	-	-
Hand weeding at (20,40 DAS)	9.181^{f} (83.8)	6.678^{e} (44.1)	7.078^{d} (49.6)	74.023^{c}	85.837^{b}	76.437^{b}
Atrazine @1000 g ha^{-1}	9.379^{e} (87.467)	5.825^{f} (33.43)	12.749^{b}(162.03)	66.050^{d}	83.560^{b}	23.093^{b}
Pendimethalin @1kg ha^{-1}	10.716^{d} (114.33)	6.268^{e} (38.8)	12.918^{b}166.37	60.377^{g}	59.950^{f}	21.003^{e}
2,4-D amine salt 580g ha^{-1}	11.573^{b} (133.43)	9.750^{b} (94.57)	6.612^{e} (43.23)	62.340^{f}	61.207^{f}	79.450^{a}
Tembotrione @120g a.i. ha^{-1}	11.284^{b}(126.833)	9.597^{b} (91.6)	7.045^{d} (49.13)	63.157^{e}	72.410^{e}	76.663^{b}
Atrazine @500 g ha^{-1} + Pendimethalin 500g ha^{-1}	11.161^{bc}(124.067)	8.1^{c} (65.133)	12.996^{b}(168.4)	60.107^{g}	71.590^{e}	20.050^{f}
Atrazine @500 g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	11.612^{b} (134.33)	8.220^{c} (67.07)	9.192^{c} (84.0)	62.900^{ef}	75.297^{d}	78.697^{ab}
Pendimethalin 500g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	11.20^{bc} (124.93)	7.67^{d} (58.33)	9.117^{c} (82.63)	80.157^{a}	89.170^{a}	60.753^{d}
Atrazine @1000 g ha^{-1} + Tembotrione @120g a.i. ha^{-1}	8.206^{h} (66.83)	5.105^{g} (25.57)	8.652^{c} (74.4)	77.900^{ab}	84.100^{b}	64.643^{c}
Pendimethalin @1kg ha^{-1}+ Tembotrione @120g a.i. ha^{-1}	8.656^{g} (74.433)	6.167^{e} (37.53)	8.540^{c} (72.43)	75.120^{b}	81.323^{c}	65.610^{c}
CD(p<0.05)	0.114	0.194	0.257	0.741	1.25	2.47

*Values in parentheses are original values as observed, while without parentheses are transformed (√x+0.5) values

weeding as an effective management strategy for *Digera arvensis.* The combination of Atrazine at 1000 g ha^{-1} and Tembotrione at 120 g a.i. ha^{-1} demonstrated optimal efficacy, decreasing biomass to 25.567 g m^{-2} and attaining a WCE of 84.10 %. Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} and Atrazine at 500 g ha^{-1} combined with Pendimethalin at 500 g ha^{-1} demonstrated effective control, yielding biomasses of 37.533 g m^{-2} and 65.133 g m^{-2}, respectively, with weed control efficiencies of 81.32 % and 71.59 %. The effective weed control results from the dual processes of photosynthetic suppression and disruption of carotenoid biosynthesis, impacting both freshly germinated and established weeds in maize (15-17).

Total weed biomass of Cyperus rotundus (g m^{-2}) and WCE % : The weedy check demonstrated a substantial total biomass of 210.9 g m^{-2} rendering *Cyperus rotundus* one of the more challenging weeds to control due to its perennial characteristics and underground tuber, which promotes its regrowth. Hand weeding substantially reduced biomass to 49.6g m^{-2} resulting in a WCE of 79.93 %. The manual weeding can control *Cyperus rotundus*, however complete eradication remains challenging due to its underground tuber propagation (18). Atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g ha^{-1} diminished biomass to 74.400 g m^{-2} resulting in a WCE of 81 %, thereby establishing it as the most efficacious chemical treatment. This combination addresses both photosynthetic mechanisms and carotenoid pathways, rendering it an effective post-emergent treatment for *Cyperus rotundus*. Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} demonstrated successful control, reducing biomass to 72.433 g m^{-2} and achieving a WCE of 78.22 %, signifying that the pre-emergence application of Pendimethalin followed by the post-emergence treatment of Tembotrione efficiently suppresses weed development (19).

Impact of different herbicide treatments on maize growth parameters

The research assessed the effects of several herbicide treatments on maize growth metrics, encompassing plant height, number of leaves per plant, leaf area, stem diameter and chlorophyll index (SPAD). The following is an analysis of the results derived from the observed data.

Plant height (cm)

The plant height exhibited considerable variation among treatments. The maximum plant height was observed in the treatment atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} (175.8 cm), closely followed by Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} (169.2 cm). The manual weeding procedure yielded a significant plant height of 165.3 cm. The shortest plants measured 110.3 cm in weedy control, indicating the detrimental effect of weed competition on plant growth. The atrazine inhibits photosystem II (PSII), hence affecting photosynthesis in vulnerable plants, whereas Tembotrione inhibits 4-hydroxyphenylpyruvate dioxygenase (HPPD), obstructing carotenoid formation (19). The utilization of pre-emergence herbicides, including Atrazine and Pendimethalin, yielded moderate outcomes, whereas combination treatments demonstrated superior efficacy compared to single applications (20).

No. of leaves

The combination of these two herbicides offers extensive control over both grass and broadleaf weeds, facilitating the taller growth of maize with diminished competition. The use of herbicides and manual weeding resulted in a rise in the number of leaves per plant, with Atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} producing the greatest count of leaves $plant^{-1}$ (12.00), followed by Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} (11.33 leaves). The weedy control had the fewest leaves (7.33), demonstrating that weed competition markedly decreased vegetative development. Pendimethalin, a mitotic inhibitor, disrupts cell division in weeds, offering superior pre-emergence control of annual grasses and broadleaf species (21). The incorporation of tembotrione improves post-emergence weed management, enabling maize to generate additional foliage due to less weed competition.

Leaf area

The treatments with Atrazine @1000 g ha^{-1} + Tembotrione @120g a.i. ha^{-1} (458.38 cm^2) and Pendimethalin @1kg ha^{-1} + Tembotrione @120g a.i. ha^{-1} (455.03 cm^2) applied had significantly greater leaf areas, which indicate the photosynthetic ability of the plants. The hand weeding treatment demonstrated a significant leaf area of 453.53 cm^2. On the other hand, the weedy control had the smallest leaf area (268.39 cm^2), illustrating the detrimental effect of weed competition on leaf growth. The combined effect of atrazine and tembotrione proficiently inhibits both grass and broadleaf weeds, hence minimizing resource competition and facilitating the development of larger leaves in maize for enhanced photosynthesis (22).

Stem girth (cm)

The treatments considerably influenced stem girth, with the combination of Atrazine at 1000 g ha^{-1} and Tembotrione at 120 g a.i. ha^{-1} yielding the thickest stem at 7.26 cm, followed by Pendimethalin at 1 kg ha^{-1} and Tembotrione at 120 g a.i. ha^{-1} at 7.17 cm. The weedy check (5.13 cm) exhibited the shortest stem, indicating that competition with weeds diminished the resources accessible for stem growth. Intensive weed management improves stem girth. The post-emergence efficacy of Tembotrione, in conjunction with the pre-emergence action of Atrazine, facilitates prolonged weed management during the maize growth cycle, leading to thicker, greater strength stems (23).

Chlorophyll index (SPAD)

The chlorophyll index, measured by the SPAD, reached its peak at Atrazine 1000 g ha^{-1} combined with Tembotrione@120 g a.i. ha^{-1} (44.8), signifying increased photosynthetic activity. This was succeeded by Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g a.i. ha^{-1} (42.2). The weedy control exhibited the lowest SPAD value (25.4), indicating that weed competition substantially hindered chlorophyll synthesis and photosynthesis. The efficacy of Tembotrione-based treatments in enhancing chlorophyll content relative to other herbicides and the control group (23). Tembotrione functions as an HPPD inhibitor, impairing carotenoid production in weeds, resulting in chlorophyll depletion and plant mortality, but maize plants thrive, accumulating increased chlorophyll levels as reported by (24).

Fresh and dry weight (g) plant

The fresh weight of maize plants exhibited significant variation among treatments, with the maximum recorded at Atrazine 1000 g ha^{-1} + Tembotrione 20g ha^{-1} (225.8 g), followed by Pendimethalin 1kg ha^{-1} + Tembotrione 120g ha^{-1} (218.3 g) and Pendimethalin 500g ha^{-1} + 2,4-D amine salt 290g ha^{-1} (217.3 g). The minimal fresh weight was observed in the weedy control (126.4 g), signifying that weed competition significantly hindered plant biomass production. The combination of Atrazine, Pendimethalin and Tembotrione is more efficacious in diminishing weed competition and encouraging biomass increase (24). The fresh weight results correspond with prior data indicating that successful weed control enhances plant vitality. The dry weight exhibited a comparable trend, with Atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g ha^{-1} yielding the maximum dry weight of 146.23 g. The weedy check again gave the lowest value (45.83 g). The significant impact of uncontrolled weed competition on maize biomass accumulation. The dry weight outcomes indicate the efficacy of herbicide combinations in enhancing maize growth by reducing competition for nutrients, water and light (25). The substantial rise in dry weight in the treated plots signifies enhanced crop performance and resource distribution.

CGR and RGR

The crop growth rate (CGR), indicating the biomass accumulation rate over time, was highest in the treatment of Atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g ha^{-1} (2.400 g m^{-2} day^{-1}), greatly exceeding all other treatments. The second-highest CGR was seen with Pendimethalin at 1 kg ha^{-1} combined with Tembotrione at 120 g ha^{-1} (1.708 g m^{-2} day^{-1}), followed by 2,4-D amine salt at 580 g ha^{-1} (1.566 g m^{-2} day^{-1}). The lowest crop growth rate (CGR) was seen in the weedy control (0.372 g m^{-2} day^{-1}), which experienced significant weed competition. The enhanced CGR noted in the Atrazine + Tembotrione combination indicates that this treatment facilitated optimal conditions for accelerated development and effective resource utilization, whereas the weedy control exhibited restricted growth due to weed competition (25). The RGR, reflecting the efficiency of plants in transforming available resources into biomass, exhibited negligible differences among the treatments and these differences were not statistically significant (NS). The maximum relative growth rate (RGR) was recorded in the treatment with Atrazine at 1000 g ha^{-1} combined with Tembotrione at 120 g ha^{-1} (0.0312 g g^{-1} day^{-1}), succeeded by Pendimethalin at 1 kg ha^{-1} with Tembotrione at 120 g ha^{-1} (0.0285 g g^{-1} day^{-1}). The weedy check exhibited the lowest relative growth rate (0.0215 g g^{-1} day^{-1}), indicating that weed competition limits the maize plants' efficacy in resource conversion for growth. Despite the RGR differences lacking statistical significance, the elevated values observed in the Atrazine + Tembotrione and Pendimethalin + Tembotrione treatments indicate that both herbicide combinations were more efficacious in enhancing relative growth efficiency (26) in case of maize crop weeds as indicated in Table 4 and 5.

Linear regression and correlation

Significant correlation exists among weed control efficiency, weed density and biomass within the same weed species, with the most apparent relationship observed between

Table 4. Effect of pre and post emergence herbicides on growth attributes of maize

Treatments	Plant height (cm)	No. of leaves plant^{-1}	Leaf area (cm^2)	Stem girth (cm)	Chlorophyll index (SPAD)
Weedy check	110.333^{f}	7.333^{e}	268.393^{i}	5.133^{e}	25.400^{g}
Hand weeding at (20,40 DAS)	165.333^{b}	11.333^{ab}	453.533^{b}	6.800^{ab}	39.833^{c}
Atrazine @1000 g ha^{-1}	136.867^{e}	8.000^{de}	364.347^{h}	5.667^{de}	33.833^{f}
Pendimethalin @1kg ha^{-1}	137.133^{e}	9.000^{cd}	384.783^{g}	5.500^{de}	34.367^{ef}
2,4-D amine salt 580g ha^{-1}	146.667^{d}	8.333^{de}	395.367^{f}	5.933^{cd}	35.433^{def}
Tembotrione @120g a.i. ha^{-1}	153.900^{c}	10.667^{ab}	412.493^{e}	5.733^{cde}	36.300^{cde}
Atrazine @500 g ha^{-1} + Pendimethalin 500g ha^{-1}	144.667^{d}	10.333^{bc}	425.233^{d}	6.000^{cd}	36.833^{cd}
Atrazine @500 g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	151.667^{c}	10.667^{ab}	424.583^{d}	6.367^{bc}	36.333^{cde}
Pendimethalin 500g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	154.700^{c}	10.333^{bc}	435.967^{c}	6.047^{cd}	37.933^{cd}
Atrazine @1000 g ha^{-1} + Tembotrione @120g a.i. ha^{-1}	175.833^{a}	12.000^{a}	458.383^{a}	7.260^{a}	44.767^{a}
Pendimethalin @1kg ha^{-1}+ Tembotrione @120g a.i. ha^{-1}	169.233^{a}	11.333^{ab}	455.033^{ab}	7.167^{a}	42.167^{b}
CD($p<0.05$)	3.66	1.368	4.257	0.618	2.091

Table 5. Effect of pre and post emergence herbicides on fresh and dry weight of maize plant

Treatments	Fresh weight (g)	Dry weight (g)	CGRgg^{-1}m^{-2}	RGRgg^{-1}m^{-1}day^{-1}
Weedy check	126.367^{e}	45.833^{h}	0.372^{f}	0.021^{a}
Hand weeding at (20,40 DAS)	214.900^{b}	136.433^{bc}	1.648^{ab}	0.028^{a}
Atrazine @1000 g ha^{-1}	195.400^{d}	91.833^{g}	0.746^{e}	0.025^{a}
Pendimethalin @1kg ha^{-1}	205.467^{c}	105.767^{f}	1.007^{d}	0.028^{a}
2,4-D amine salt 580g ha^{-1}	216.467^{b}	106.600^{f}	1.566^{ab}	0.027^{a}
Tembotrione @120g a.i. ha^{-1}	207.267^{c}	116.000^{e}	1.389^{bc}	0.028^{a}
Atrazine @500 g ha^{-1} + Pendimethalin 500g ha^{-1}	209.333^{c}	123.633^{d}	1.595^{ab}	0.027^{a}
Atrazine @500 g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	214.700^{b}	132.233^{c}	1.315^{c}	0.027^{a}
Pendimethalin 500g ha^{-1} + 2,4-D amine salt 290g ha^{-1}	217.333^{b}	134.067^{c}	1.198^{cd}	0.026^{a}
Atrazine @1000 g ha^{-1} + Tembotrione @120g a.i. ha^{-1}	225.833^{a}	146.233^{a}	2.400^{a}	0.031^{a}
Pendimethalin @1kg ha^{-1}+ Tembotrione @120g a.i. ha^{-1}	218.333^{b}	140.133^{b}	1.708^{ab}	0.028^{a}
CD(p<0.05)	4.762	4.264	0.205	NS

weed control efficiency and weed biomass as shown in Fig. 2. Nevertheless, interspecies correlations among factors associated with various weeds are predominantly non-significant, suggesting specific to a species dynamic in weed management. Fig. 3, 4, 5 Left plot: Displays a negative correlation between WCE % and weed density. As the weed control efficiency increases, the weed density decreases, indicating effective control of weed. Right plot: Displays a positive correlation between Weed biomass and weed density as represented in Table 6. As weed biomass increases, weed density also increases, showing a direct relationship between biomass and density. The shaded regions represent confidence intervals, suggesting high confidence in these relationships.

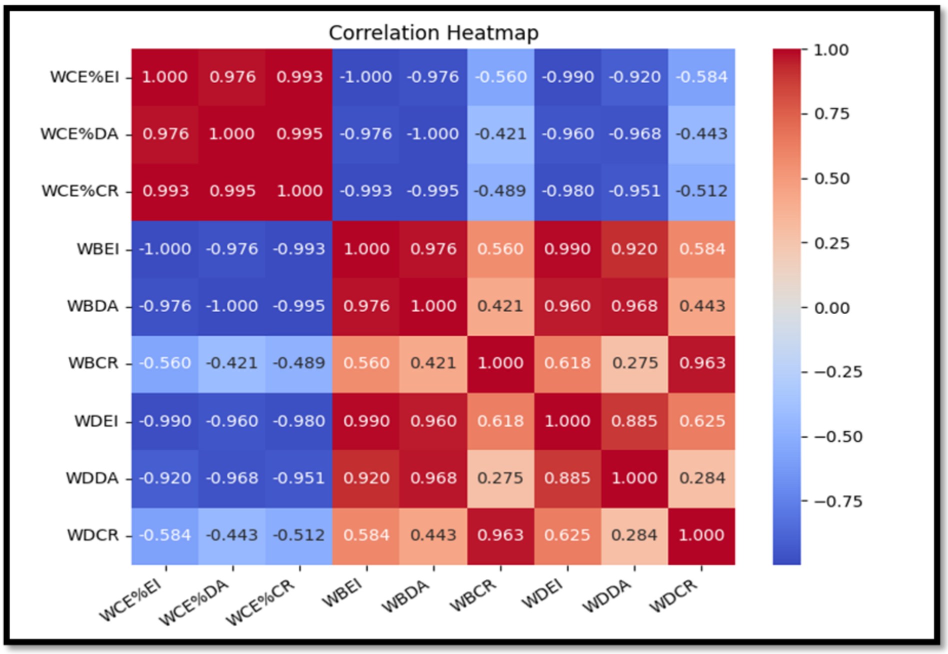

Fig. 2. Correlation heat map of weed density, WCE % And weed biomass of different species.

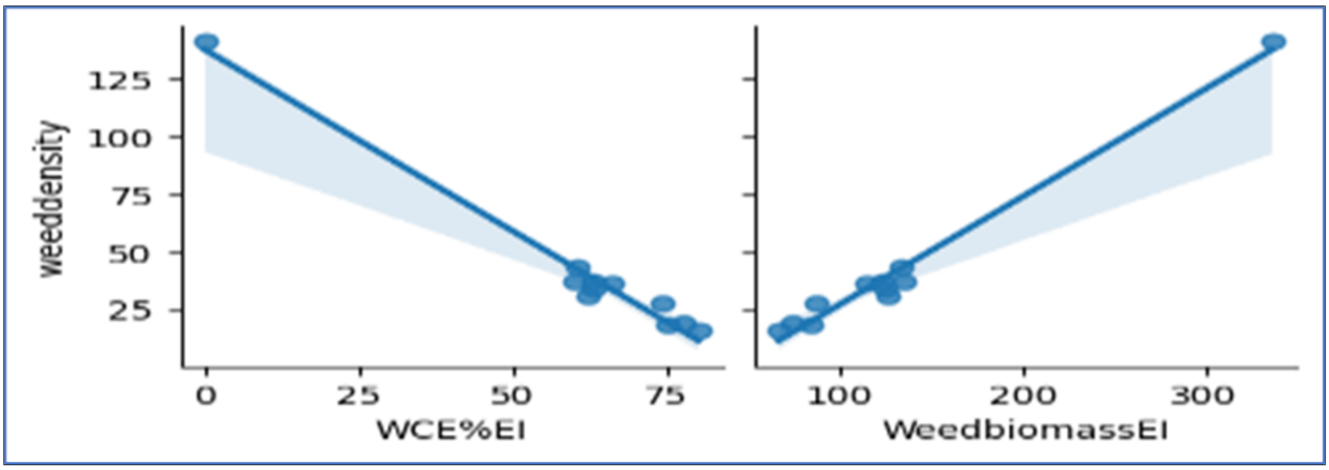

Fig. 3. image shows two scatter plots that visualize the relationships between weed density and two variables: WCE %EI (Weed Control Efficiency for *Eleusine indica*) and Weed biomass EI (Weed biomass for *Eleusine indica*).

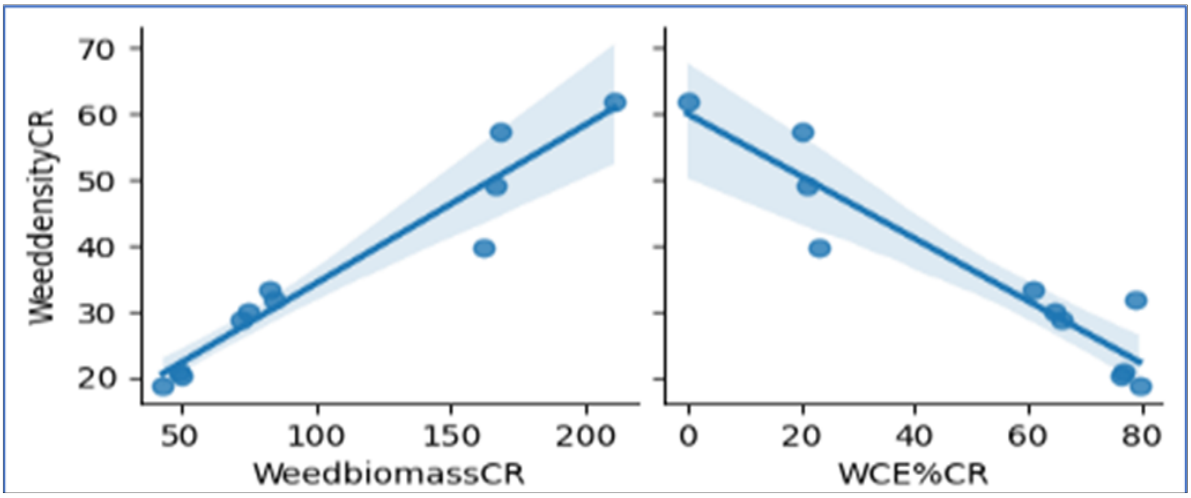

Fig. 4. This image shows two scatter plots that illustrate the relationships between Weed density CR (weed density for *Cyperus rotundus*) and two other variables: Weed biomass CR (weed biomass for *Cyperus rotundus*) and WCE % CR (Weed Control Efficiency for *Cyperus rotundus*).

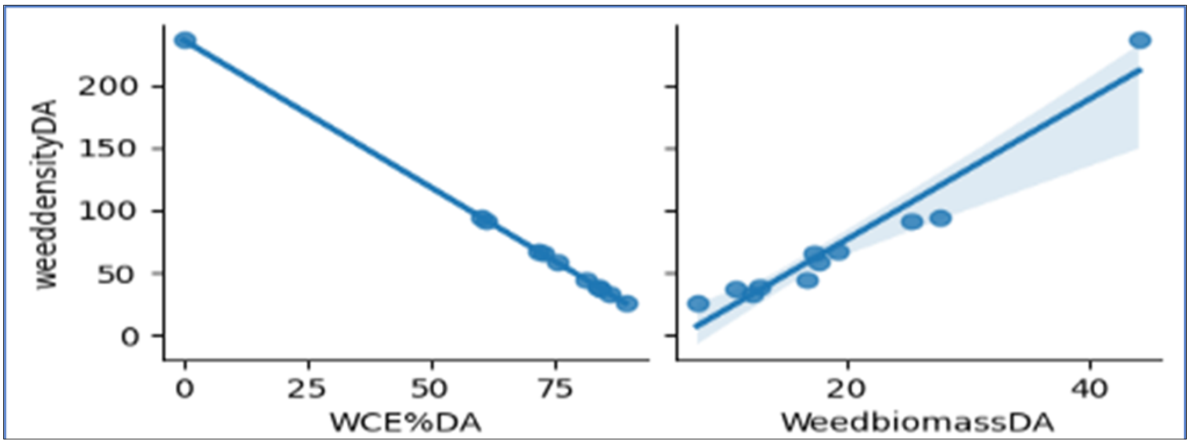

Fig. 5. This image presents two scatter plots that illustrate the relationships involving weed density DA (weed density for *Digera arvensis*), WCE % DA (Weed Control Efficiency for *Digera arvensis*) and Weed biomass DA (weed biomass for *Digera arvensis*).

Table 6. Correlation table between the different weed parameters

	WDEI	WDDA	WDCR	WBEI	WBDA	WBCR	WCEEI	WCEDA	WCECR
WDEI	1	0.885***	0.626*	0.99***	0.96***	0.618*	-0.99***	-0.96***	-0.597
WDDA	0.885***	1	0.285	0.92***	0.968***	0.275	-0.92***	-0.968***	-0.262
WDCR	0.626*	0.285	1	0.584	0.443	0.963***	-0.584	-0.443	-0.939***
WBEI	0.99***	0.92***	0.584	1	0.976***	0.56	-1***	-0.976***	-0.531
WBDA	0.96***	0.968***	0.443	0.976***	1	0.421	-0.976***	-1***	-0.408
WBCR	0.618*	0.275	0.963***	0.56	0.421	1	-0.56	-0.421	-0.982***
WCEEI	-0.99***	-0.92***	-0.584	-1***	-0.976***	-0.56	1	0.976***	0.531
WCEDA	-0.96***	-0.968***	-0.443	-0.976***	-1***	-0.421	0.976***	1	0.408
WCECR	-0.597	-0.262	-0.939***	-0.531	-0.408	-0.982***	0.531	0.408	1

***Correlation is significant at 0.001 level (two tailed) , **Correlation is significant at 0.01 level (two tailed) , * Correlation is significant at 0.05 level (two tailed)

Conclusion

The herbicide combination of Atrazine at 1000 g ha^{-1} and Tembotrione at 120 g a.i. ha^{-1} proved to be the most effective chemical treatment across every parameter. This combination yielded the lowest weed density and biomass while enhancing maize growth indicators, including plant height, leaf area, stem girth and chlorophyll index. The dual-action mechanism-Atrazine's inhibition of photosystem II and Tembotrione's disruption of carotenoid biosynthesis-demonstrated significant effectiveness in managing both grass and broadleaf weeds, therefore enhancing maize development by reducing resource competition. Pendimethalin combined with Tembotrione exhibited substantial performance in weed control, especially in the management of *Digera arvensis* and *Cyperus rotundus*, indicating its potential as a viable choice for integrated weed management.

Acknowledgements

Authors are highly thankful for the Lovely Professional University for funding to conduct the research and all the authors are showing no conflict interest.

Authors' contributions

AG, PSG and ZAS did work in the field. K and SS wrote the paper, ST did the analysis and AS and IF did the corrections.

Compliance with ethical standards

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

Ethical issues: None

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