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Research article

Integrated weed management practices for effective weed control and quality fodder production in sorghum and cowpea under rainfed conditions

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Abstract
Identification of appropriate and efficient weed management tactics is a continuous process in order to cope with the emergence of new weed species and weed shifts in any cropping system. Therefore, a study was conducted to screen suitable herbicides and develop integrated weed management tactics for forage sorghum and cowpea. The bioassay and field study results suggested that oxadiargyl for sorghum and imazethapyr for cowpea exhibited selectivity and effectively controlled the weeds. The former could be used as an alternative herbicide to conventional atrazine and atrazine + pendimethalin herbicides for sorghum and the latter for pendimethalin and alachlor herbicides for cowpea. The integrated weed management study further demonstrated that Pre-application of oxadiargyl alone and Pre-application of oxadiargyl followed by manual weeding at 40 DAS for sorghum and PRE-application of imazethapyr alone and PRE-application of imazethapyr and Pre-application of imazethapyr followed by manual weeding for cowpea was effective in controlling broad spectrum weeds and resulted in higher green fodder yield.

Keywords: Bioassay study, Forage crops, Herbicide, Integrated weed management

Introduction
Cowpea [*Vigna unguiculata* (L.) Walp] and sorghum [*Sorghum bicolor* (L.) Moench] are the major rainy season forage crops for fodder security of millions of cattle in semi-arid tropics (Gupta *et al*., 2016; Mahanta *et al*., 2020). Both are widely cultivated crops in low to marginal fertile lands of India (Kumawat *et al*., 2021). Fodder cowpea and sorghum are grown in around 0.3 and 2.6 million ha, respectively (Anonymous, 2021). Cowpea is a versatile crop that serves as food grain, forage, and cover crop and enhances soil fertility by fixing atmospheric nitrogen (N). The rate of N fixation varies from 74 to 116 kg ha^{-1}; crop management practices and varieties may influence it. Cowpea is also referred to as vegetable meat due to its high protein content (19–26%). It is generally cultivated in the summer (April-June) with supplemental irrigation and during the rainy season (July-September) purely as a rainfed crop in semi-arid regions. Sorghum is also a versatile crop, used as food grain and fodder in drought-prone regions around the world. It is the fifth most important cereal crop after wheat, rice, maize, and barley in the world (Peerzada *et al*., 2017). Sorghum is a major crop in South Asia, Africa, and Central America. Its residue has also been used as building materials and as fuel for cooking in semi-arid regions of the world.

Cowpea and sorghum are rainy-season crops and both crops produce a high quantity of nutritious fodder (Ghani *et al*., 2015). In general, rainy-season crops like cowpea and sorghum have been severely impacted by weeds due to the early soggy growth of crops (Govindasamy *et al*., 2021). Weeds are a major pest in tropical and humid areas, where excessive precipitation, temperature, and humidity are expected to promote their growth. Critical weed-free periods for both cowpea and sorghum are between 30 to 40 days after emergence. For example, the critical weed-free period for cowpeas in rainy conditions was 20 to 30 days, but weeds present beyond this period did not affect yield (Manibharathi *et al*., 2024). In the case of sorghum, the low weed density early in the crop season may affect crop yield. However, the high density of grasses after 2 weeks of crop emergence reduced the yield by 20%. Weed infestation throughout the crop season results in substantial loss of quality and yield of cowpea and sorghum. Lack of weed control leads to 12.7–60.0% yield loss in cowpeas (Frenda *et al*., 2013). The yield loss is higher for cowpeas when grown for seed production (90%) (Parmar *et al*., 2022). The estimated loss of green forage yield due to weeds in sorghum varies between 22.8 to 75% (Gharde *et al*., 2018). Yield loss estimates for cowpea and sorghum vary with cultivars, row spacing, seeding time, type of weed species, and environmental conditions (Vaishnavi and Manisankar, 2022).

The current method of weed control in fodder cowpea and sorghum is hand weeding. Both the crops required a minimum of two hand weeding, one at 20 days after sowing (DAS) and another at between 40 to 50 DAS. Two times weeding a hectare requires 25 to 50 man-days costing around Rs. 200000. The primary reason for adopting the traditional hand weeding for forage crops is the fear of herbicide residue transfer from fodder to milk and meat. Green fodder is the major source of animal feed in India. Thus, livestock keepers are very skeptical about the use of herbicides. The major drawback of manual hand weeding is the availability of labor. In recent times, agricultural laborers are moving to locally accessible industrial jobs, government-sponsored schemes, and urban areas for a better life. According to World Bank estimation, agricultural employment has declined from 54% in 2010 to 38% in 2020 (Anonymous, 2022). It clearly indicates that in the future Indian agriculture should depend on machinery or chemicals to avoid dependence on labor.

Therefore, it is very much essential to identify suitable herbicides for forage crops (Kantwa *et al*., 2023). Currently, very few herbicides have been recommended for cowpea and sorghum. The herbicides currently used for fodder cowpea are pendimethalin, imazethapyr, alachlor, and butachlor and for sorghum, atrazine, pendimethalin, and 2,4-D (Gupta *et al*., 2016). In this study, we have examined the selectivity of various herbicides [for cowpea, imazethapyr + pendimethalin (Tank mix), propaquizafop, quizalofop-p-ethyl, quizalofop-ethyl + oxyfluorfen (Tank mix), imazethapyr + imazamox (ready mix) and for sorghum, oxadiargyl and atrazine + pendimethalin (tank mix)] that have been recommended for other cereals and pulses (Table 1).

Chemical weed management alone is not a solution for successful weed management. Integration of one or more integrated weed management (IWM) tools with herbicides is a driver of sustainable integrated pest management (Riemens *et al*., 2022). The primary aim of the IWM framework is to manage weeds for more than one season (Gupta *et al*., 2022). Thus, the integration of mechanical weed management methods like hand weeding and hoeing was also tried. The hypothesis of this study was that the herbicides used in other cereal and pulse crops would also be selective to fodder sorghum and cowpea. The objectives were (i) screening of different herbicides for fodder sorghum and cowpea and (ii) development of integrated weed management practices for fodder sorghum and cowpea under rainfed conditions in the semi-arid tropics of India.

Materials and Methods

***Study area*:** The experiments were conducted from 2014 to 2017 (4 years) at the Indian Grassland and Fodder Research Institute (IGFRI), Jhansi, India, to check the selectivity of different herbicides and develop an integrated weed management program for fodder cowpeas and sorghum. Weather parameters (i.e., the maximum temperature, minimum temperature, and rainfall) were recorded for the years 2014-2017 (Table 2). The maximum and minimum air temperatures and rainfall were within the long-term average limit of the study location. However, the maximum temperature and rainfall were considerably higher (~2°C) and lower (31.4–155 mm), respectively, compared to the long-term average of the location in the year 2016. Moreover, delayed onset of rainfall and below the long-term average rainfall received for the month of June (18.5 mm) in the year 2014 were the features of rainfall during the study period.

Experiment 1: Screening of herbicides for fodder cowpea and sorghum

***Laboratory screening (bioassay study)*:** A laboratory experiment was conducted to verify the dose selectivity (three levels) of some of the common herbicides used in major cereal (atrazine, pendimethalin, oxadiargyl, and a combination of atrazine and pendimethalin) and pulse crops (imazethapyr, pendimethalin, and alachlor) in India. Experiments were conducted from July to September 2014, using sterile Petri dishes with 9 cm diameter. Twenty seeds of forage sorghum and cowpea were placed between two sterilized filter papers (Whatman No. 1) in the petri dish. Three doses (area basis) of atrazine (0.5, 0.75, and 1.0 kg a.i. ha^{-1}), pendimethalin (0.75, 1.0, and 1.5 kg a.i. ha^{-1}), oxadiargyl (0.75, 1.0, and 1.5 kg a.i. ha^{-1}), and combination of atrazine and pendimethalin (0.5+0.75, 0.75+0.50, and 1.0+1.0 kg a.i. ha^{-1}) were applied to Petridishes immediately after placing sorghum seeds. Likewise, three doses of imazethapyr (0.1, 0.15, and 0.2 kg a.i. ha^{-1}), pendimethalin (0.5, 0.75, and 1.0 kg a.i. ha^{-1}), and alachlor (0.75, 1.0, and 1.5 kg a.i. ha^{-1}) were applied to each petri dishes immediately after placing cowpea seeds. Nutrients were applied as per the recommended practices; at basal 60: 40: 40 kg of N: P_2O_5: K_2O doses ha^{-1} were applied at the time of sowing and reaming N (30 kg N ha^{-1}) was top-dressed at one month

Table 1. Chemistry of herbicides used in this study

Herbicide	Family	Chemistry	Mode of action	Uses
Imazethapyr	Imidazolinones	2-[4,5 dihydro-4-methyl-4-(1-methyethyl)-5oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid	Acetolactate synthase (ALS)inhibitors	Broad-spectrum herbicides recommended for soybean, edible legumes, peanuts, alfalfa, etc (Shaner, 2014).
imazamox	Imidazolinones	2-[4,5 dihydro-4-methyl-4-(1-methyethyl)-5oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)3-pyridinecarboxylic acid	Acetolactate synthase (ALS)inhibitors	Broad-spectrum herbicides recommended for soybean, edible legumes, peanuts, alfalfa, etc (Shaner, 2014).
Pendimethalin	Dinitroaniline	*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenxenamine	Microtubule assembly inhibitors	A broad spectrum herbicide (mainly a grass killer but also controls small-seeded broadleaf weeds) recommended for sweet corn, grain sorghum, cotton, potatoes, peas, etc (Shaner, 2014).
Propaquizafop	Aryloxyphenoxy-propionate	2-[[(1-methyleethylidene) amino]oxy]ethyl(2R)-2-[4-[6-Chloro-2quinoxalinyl]oxy] phenoxy	Acetyl CoA Carboxylase (ACCase) inhibitor	Grass killers recommended for soybean, cotton, peanut, vegetables, oilseeds, etc (Shaner, 2014)
Quizalofop-p-ethyl	Aryloxyphenoxy-propionate	2R-2-[4-[(6-chloro-2-quinoxalinyl)oxy]pheno] propanoic acid	Acetyl CoA Carboxylase (ACCase) inhibitor	Grass killers recommended for soybean, cotton, peanut, vegetables, oilseeds, etc (Shaner, 2014)
Oxyfluorfen	Diphenyl ether	2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl) benzene	Protoporphyrinogen oxidase inhibitor	A broad-spectrum herbicide (small-seeded broadleaf and suppress annual grasses) recommended for corn, cotton, vegetables, onions, etc (Shaner, 2014).
Oxadiargyl	Oxadiazole	3-[2,4-dichloro-5-(20propynyloxy)phenyl]-5-(1,1-dimethylethyl)-1,3,4-oxadiazol-2(3*H*)-one	Protoporphyrinogen oxidase inhibitor	A broad-spectrum herbicide recommended for rice, winter wheat, sunflower, etc (Shaner, 2014).

after sowing. Urea, SSP, and MOP (KCL) were used as a source of N, P_2O_5, and K_2O.

Field screening**:** The field experiments were carried out during the rainy season of 2014 and 2015. The soil characteristics of sorghum field experiments (25°31', 21.4 ''N and 78°33', 48.2''E, MSL 233 m) were sandy loam soil (pH 6.6) with available N, P, and K nutrient status, respectively, 110 kg, 17.02 kg, and 197.12 kg ha^{-1} (Kantwa *et al*., 2020). The fodder cowpea was grown (25°29′ 48.4′′ N,78°33′35.6′′ E, MSL 233 m) in a clay loam soil (pH 7.6) with available N of 202 kg ha^{-1}, P of 9.64 kg, and K of 249 kg (Govindasamy *et al*., 2021). The experiments of both sorghum and cowpea were laid out in a completely randomized design with four replications. The sorghum treatments consist of oxadiargyl at 0.09 kg a.i.ha^{-1} [pre-emergence (PRE at 3 days after sowing (DAS))], bispyribac sodium at 0.02 kg a.i.ha^{-1}as a [post-emergence (POST, 20 DAS)], 2,4-D EE at 1 kg a.i.ha^{-1} + atrazine at 0.75 kg a.i.ha^{-1}(POST), oxadiargyl at 0.09 kg a.i.ha^{-1} (PRE) followed by 2,4- D EE at 1 kg a.i.ha^{-1} (POST), fenoxaprop-p-ethyl at 0.08 kg a.i.ha^{-1}+ 2,4 -D EE at 1 kg a.i.ha^{-1}(POST), pendimethalin at 0.75 kg a.i.ha^{-1}(PRE), atrazine at 0.75 kg a.i.ha^{-1}(PRE), atrazine at 0.75 kg a.i.ha^{-1}+ pendimethalin at 0.75 kg a.i.ha^{-1}(PRE), weed-free check (WFC), weedy check (WC). The cowpea treatments consist of pendimethalin 0.75 kg a.i.ha^{-1}(PRE), imazethapyr 0.1 kg a.i.ha^{-1}(PRE), alachlor 1 kg a.i. ha^{-1}(PRE), quizalofop-ethyl 0.4 kg a.iha^{-1}(POST), imazethapyr + pendimethalin 800 mlha^{-1}(POST), propaquizafop 750 mlha^{-1} (POST), quizalofop-ethyl 0.4 kg + oxyfluorfen 0.25 kg a.i. ha^{-1} (POST), and imazamox + imazapyr 30g a.i. ha^{-1} (POST). The PRE and POST herbicides were sprayed on 3 and 20 days after sowing, respectively, using a battery-operated backpack sprayer (ASPEE V-DYUT DELUXE, ASPEE Enclave, Mumbai west, MH, India) (Hatzininikolaou *et al*., 2004). Weeds were manually removed at 25-day intervals to keep weed-free in WFC plots. Nutrients were applied as per the recommended practices; at basal 60: 40: 40 kg of N: P_2O_5: K_2O doses ha^{-1} were applied at the time of sowing and reaming N (30 kg N ha^{-1}) was top-dressed at one month after sowing. Urea, SSP, and MOP (KCL) were used as a source of N, P_2O_5, and K_2O.

Experiment 2: Integrated weed management for fodder cowpea and sorghum: The field experiments were carried out during the rainy season of 2016 and 2017 in the same field where the herbicide screening

Table 2. Monthly maximum and minimum temperature, and the total rainfall during the study period

Year	June	July	Aug	Sept	Oct
Maximum temperature (°C)					
2014	41.9	34.0	31.3	33.0	34.3
2015	37.6	32.2	31.3	34.1	31.2
2016	42.0	36.1	34.1	33.3	34.0
2017	40.2	34.1	33.4	36.2	35.0
Long-term average	39.8	34.0	32.2	33.2	33.5
Minimum temperature (°C)					
2014	29.4	26.1	25.2	30.5	16.0
2015	26.2	25.0	24.7	24.1	20.2
2016	26.4	26.1	24.9	23.1	17.7
2017	26.4	25.4	24.6	23.2	18.4
Long-term average	27.2	24.8	23.9	22.4	18.4
Rainfall (mm)					
2014	18.5	390.0	217.6	100.8	0
2015	149.2	437.2	527.6	43.4	107.6
2016	81.8	164.8	86.8	174	0
2017	67.2	215.2	285.2	16.6	34
Long-term average	98.7	311.6	252.5	147.8	31.4

Source: Meteorological observatory, Division of Crop Production, ICAR-IGFRI, Jhansi, India

studies were done. The integrated weed management experiments of sorghum and cowpea were laid out in a randomized block design with three replications. The most effective herbicide treatments from the screening experiments and one manual weeding were tried for these experiments. The sorghum treatments consist of oxadiargyl at 0.09 kg a.i.ha^{-1} [pre-emergence (PRE)], oxadiargyl at 0.09 kg a.i.ha^{-1}(PRE) followed by manual weeding at 40 DAS (POST), weed-free check (WFC), and weedy check (WC). The cowpea treatments consist of imazethapyr 0.1 kga.i.ha^{-1} [pre-emergence (PRE)], imazethapyr (PRE) followed by manual weeding, weed-free check (WFC), and weedy check (WC). The PRE and POST herbicides were sprayed on 3 and 20 days after sowing, respectively, using a battery-operated backpack sprayer (ASPEE V-DYUT DELUXE, ASPEE Enclave, Mumbai west, MH, India) (Hatzininikolaou *et al*., 2004). Weeds were manually removed at 25-day intervals to keep weed-free in WFC plots. Nutrients were applied as per the recommended practices; at basal 60: 40: 40 kg of N: P_2O_5: K_2O doses ha^{-1} were applied at the time of sowing and reaming N (30 kg N ha^{-1}) was top-dressed at one month after sowing. Urea, SSP, and MOP (KCL) were used as a source of N, P_2O_5, and K_2O.

***Crop and weed injury rating*:** Herbicide injury rating on crops and weeds was done by noting the yellowing, discoloration, necrosis, and crop stunt on 7 and 21 days after spray (DAS). On the rating scale, 0 indicates no crop and weed injury and 100 indicates severe injury in both.

Statistical analysis: All the recorded laboratory and field experiments data were subjected to analysis of variance (ANOVA). The normality of the data was verified using the Shapiro-Wilk test in the Statistical Analytical System (SAS 9.3). Non-normal data ($p < 0.05$) were subjected to square root transformation ($\sqrt{x}+1$) before performing the ANOVA test (Prabhu and Palsaniya, 2016). The laboratory study data were analyzed using a completely randomized design. While analyzing the field data (analyzed in randomized complete block design), the treatments and years were kept as fixed effects and replication as a random effect. Mean separation was done using Fisher's LSD ($p = 0.05$) for all the significant data to know the best treatment. All the graphs were made using the trial version of Sigmaplot (v14).

Results and Discussion

Screening of herbicides for fodder sorghum and cowpea at the laboratory

***Bioassay* study:** The laboratory bioassay investigation demonstrated that atrazine and oxadiargyl had higher selectivity to fodder sorghum at all the application rates than pendimethalin and the combination of atrazine and pendimethalin (Table 3). Herbicide treatments had no effect on sorghum seed germination. However, the use of pendimethalin and the combination of atrazine and pendimethalin resulted in decreased sorghum root and shoot length compared to other herbicide treatments. It seems that pendimethalin has some selectivity concerns in the petri dish conditions. The distinctive club-root symptom in sorghum at 7 days after the bioassay study further shows that pendimethalin has some selectivity concerns even at the lower dose. This can be explained based on the mode and site of action of the herbicides used in this study. Atrazine and oxadiargyl inhibit photosystem II and protoporphyrinogen oxidase, respectively, whereas pendimethalin and combinations of atrazine and pendimethalin inhibit mitosis and photosystem II (Hatzininikolaou *et al*., 2004). Therefore, the injury symptom was only observed with pendimethalin. The higher root and shoot length reduction caused by all concentrations of pendimethalin and a combination of atrazine + pendimethalin could be attributed to reduced volatilization and photo-decomposition as a result of low light exposure under lab conditions (Hatzininikolaou *et al*., 2004). For cowpeas, all the herbicides showed a greater selectivity except pendimethalin at a higher rate. Cowpea root and shoot length were higher for control, followed

Table 3. Effect of different herbicides and their doses on root length, shoot length and germination of fodder sorghum

Treatments	Root length (cm)	Shoot length (cm)	Germination (%)
Atrazine 0.50 kg	1.82a	2.17b	40.62a
Atrazine 0.75 kg	2.52a	3.44a	46.50a
Atrazine 1.0 kg	2.40a	4.14a	45.74a
Oxadiargyl 0.07 kg	1.81a	4.07a	47.88a
Oxadiargyl 0.08 kg	1.98a	3.95a	47.89a
Oxadiargyl 0.09 kg	2.10a	2.72b	45.87a
Pendimethalin 0.50 kg	0.37b	0.63c	47.95a
Pendimethalin 0.75 kg	0.30b	0.47c	45.72a
Pendimethalin 1.0 kg	0.40b	0.64c	50.19a
Atrazine 0.50 kg +Pendimethalin 0.75 kg	0.35b	0.33c	48.03a
Atrazine 0.75 kg + Pendimethalin 0.50 kg	0.35b	0.43c	50.97a
Atrazine 1.00 kg +Pendimethalin 1.00	0.42b	0.57c	49.38a
Control	2.54a	4.28a	56.82a
p-value	0.005	0.04	NS

by imazethapyr at a higher rate. The alachlor treatment resulted in the lowest root length compared to other treatments. Shoot length was almost similar across the treatments except for imazethapyr at 0.2 kg a.i. ha^{-1}. The tolerance of fodder cowpeas to imazethapyr is most likely owing to the plant's ability to convert toxic metabolites to non-toxic metabolites (Baerg and Barrett, 1996).

Field screening of herbicides for fodder sorghum and cowpea

Phytotoxicity ratings for field screening study: Phytotoxicity rating of crops indicates that oxadiargyl and fexoxaprop-p-ethyl on sorghum and pendimethalin, quizalofop-ethyl, the tank mix of quizalofop-ethyl + oxyfluorfen, and the ready mix imazethapyr + imazamox on cowpea caused yellowing, necrosis, and stunting of crops at 7 days after application (DAA). However, most of them recovered at 21 DAS except for the application of fenoxaprop-p-ethyl on sorghum (Table 4). Atrazine and pendimethalin are popular herbicides for grain sorghum; hence, fodder sorghum might also have a similar level of tolerance to the same herbicides (Kumar *et al*., 2008). However, for the first time, our study found oxadiargyl tolerance in sorghum.In sorghum, pre-emergence (PRE) application of oxadiargyl, atrazine, and atrazine + pendimethalin; post-emergence (POST) application of 2,4-DEE + atrazine, and sequential application of oxadiargyl followed by 2,4 DEE provided broad-spectrum weed control. The range of weed injury was 85 to 95% at 21 DAS. All the herbicides mentioned above are broad-spectrum in nature thus they showed greater weed injury (Kumar *et al*., 2008). PRE-application of imazethapyr and alachlor, and POST-application of tank mix of imazethapyr + pendimethalin, and the ready mix of imazethapyr + imazamox showed a greater broad-spectrum weed injury (80–90%) in cowpea. Several studies previously reported that imazethapyr, alachlor, the tank mix of imazethapyr + pendimethalin, and the ready mix of imazethapyr + imazamox showed a higher rate of injury to weeds in different pulse crops (Kumar *et al*., 2012).

***Effect of herbicides on weed control and yield of fodder sorghum and cowpea*:** Herbicide treatments influenced the weed density, weed dry weight, and green fodder yield of fodder sorghum and cowpea (p <0.05, Table 5; Fig 1-3). The year also had an effect on the above-mentioned parameters of cowpea, but only limited to weed density and dry weight in sorghum (p <0.05). The interaction of year-by-herbicide treatments did not influence the weed density, weed dry weight, and green fodder yield of fodder sorghum and cowpea (p >0.05, Table 5). The grassy weeds such as *Echinochloa colona* (L.) Link, *Cynodon dactylon* (L.) Pers., *Digitaria sanguinalis* (L.) Scop., and *Dactyloctenium aegyptium* (L.) Willd., broadleaved weeds like *Commelina benghalensis* L., *Digera arvensis* Forssk., *Catharanthus pusillus* (Murray) G. Don, *Leucas aspera* (Willd.) Link, *Cleome viscose* L., and *Celosia argentea* L. and sedge-like *Cyperus rotundus* L. were the dominant weeds of both fodder sorghum and cowpea. Previous studies also reported a similar kind of weeds in fodder sorghum and cowpea (Rao *et al*., 2007). Tank mix of atrazine + pendimethalin decreased the total weed density (588 density m^{-2}), followed by atrazine-2,4-D EE, oxadiargyl, and atrazine. Application of oxadiargyl - 2,4-D EE resulted in the lowest weed dry weight (206.2 g m^{-2}) followed by oxadiargyl and the tank

Table 4. Phytotoxicity rating on crops and weed

Herbicides	Time (DAS†)	Dose	Crop injury† (%)		Weed injury† (%)	
		kg ai ha^{-1}	7 (DAA†)	21 (DAA)	7 (DAA)	21 (DAA)
Fodder Sorghum						
Oxadiargyl	3	0.09	50	20	70	85
Pendimethalin	3	0.75	0	0	70	75
Atrazine	3	0.75	0	0	90	95
Atrazine + Pendimethalin	3	0.50 + 0.75	0	0	90	95
Oxadiargyl - 2,4 D EE†	3 and 20	0.09-1	50†	20†	80	90
Bispyribac Sodium	20	0.025	0	0	25	25
2,4 D EE + Atrazine	20	0.75 + 0.50	0	0	90	95
Fenoxaprop-p-ethyl + 2,4-D EE†	20	0.08 + 0.75	75†	75	25	25
Fodder Cowpea						
Pendimethalin	3	0.75	25	5	50	50
Imazethapyr	3	0.1	5	5	90	90
Alachlor	3	1.0	5	5	80	80
Quizalofop-ethyl	20	0.4	25	5	80	80
Imazethapyr + Pendimethalin (tank mix)	20		25	5	80	80
Propaquizafop	20		25	10	80	80
Quizalofop-ethyl + Oxyfluorfen (tank mix)	20	0.4 + 0.25	25	10	80	75
Imazethapyr + Imazamox (ready mix)	20	0.3	25	10	80	80

†DAS: days after sowing, **DAA:** days after application; Crop injury rating is only for oxadiargyl and fexoxaprop-p-ethyl; Crop and weed injury rating scale 0-100; Observation includes crop stand, discoloration, Chlorosis, and necrosis (Crop injury: 0 indicates no injury and 100 indicates complete kill; Weed injury: 0 indicates poor weed control and 100 indicates excellent control)

Table 5. Effect of different herbicide treatments on total weed density and dry weight, and green fodder yield of fodder sorghum

Treatments	Weed density (no m^{-2})	Weed dry weight (g m^{-2})	Green fodder yield (t ha^{-1})
Year			
2014	999 (±84.9)a	263.8 (±15.0)a	22.3 (±0.54)a
2015	849 (±72.1)b	224.2 (±13.5)b	21.2 (±0.53)a
P value	<0.001	0.01	0.08
Herbicides			
Oxadiargyl	958 (±75.5)cd	216.2 (±10.0)c	20.8 (±0.69)ab
Pendimethalin	1348 (±55.9)b	309.2 (±12.3)ab	15.6 (±0.75)ef
Atrazine	992 (±66.2)cd	289.8 (±10.5)ab	18.6 (±0.87)bc
Atrazine + Pendimethalin	588 (±69.9)f	270.5 (±16.1)bc	20.2 (±0.76)ab
Oxadiargyl - 2,4 D EE	1018 (±46.5)cd	206.2 (±13.0)c	19.4 (±0.75)bc
Bispyribac Sodium	1092 (±66.8)c	257.3 (±37.0)bc	16.9 (±0.81)cde
2,4 D EE +Atrazine	893 (±65.8)de	302.2 (±33.6)ab	17.9 (±0.79)bcd
Fenoxaprop-p-ethyl + 2,4-D EE	747 (±30.0)e	242.2 (±48.7)c	16.8 (±1.17)cde
Weed free control	0 (±0)g	0 (±0)d	21.9 (±0.27)a
Unweeded control	1602 (±72.1)a	346.1 (±14.7)a	16.3 (±0.67)de
P value	<0.001	<0.001	<0.001
Year × Herbicides	0.89	0.99	0.81

Table 6. Effect of integrated weed management strategies on total weed density and dry weight, weed control efficiency, and green fodder yield of fodder sorghum

Treatments	Weed density (number/m^{-2})	Weed dry weight (g m^{-2})	Weed control efficiency (%)	Green fodder yield (t ha^{-1})
Herbicides				
Oxadiargyl	242.6 (±26.0)b	77.8 (±13.5)b	48.5 (±3.2)c	23.9 (±0.65)b
Oxadiargyl - Hand weeding	174.4 (±17.1)c	58.6 (±10.8)b	60.0(±2.6)b	25.6 (±1.12)ab
Weed free control	0 (±0)d	0 (±0)d	100 (±2.9)a	26.8 (±0.73)a
Unweeded control	389.7 (±34.9)a	146.9 (±25.8)a	0 (±0)d	19.4 (±0.69)c
P value	<0.001	<0.001	<0.001	<0.001
Year	0.17	0.92	0.50	1.00
Year × Herbicides	0.68	0.93	0.29	1.00

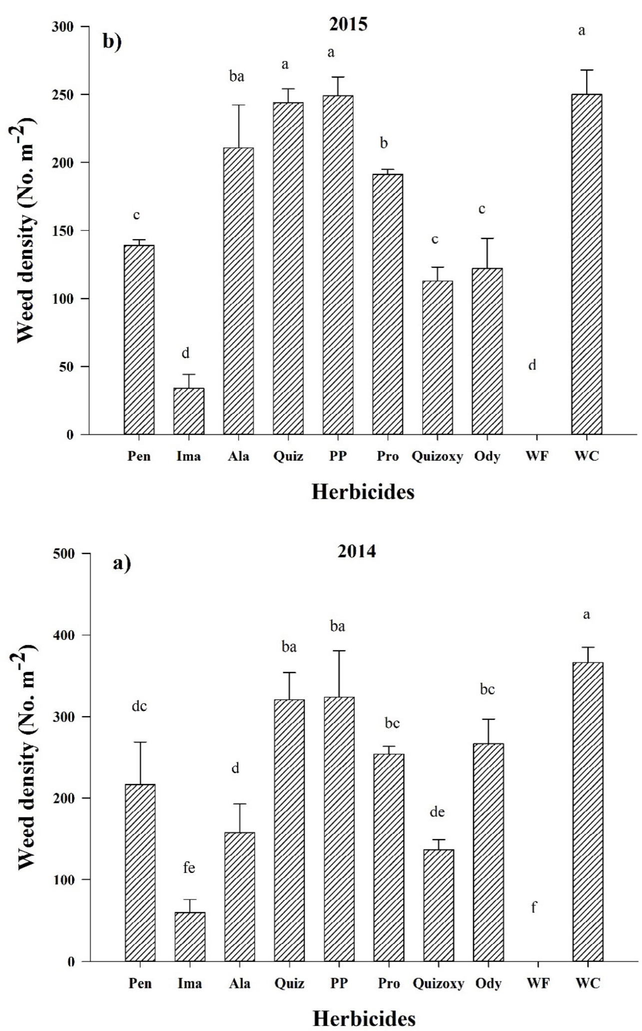

Fig 1. Total weed density influenced by the herbicide application in fodder cowpea during 2014 (a) and 2015 (b) [Pen: pendimethalin; Ima: imazethapyr; Ala: alachlor; Quiz: quizalofop-p-ethyl; PP: tank imazethapyr + pendimethalin; Prop: propaquizafop; QuizOxy: tank mix quizalofop-p-ethyl and oxyflourfen; Ody: ready-mix imazamox + imazapyr; WF: weed free and WC: weedy control]

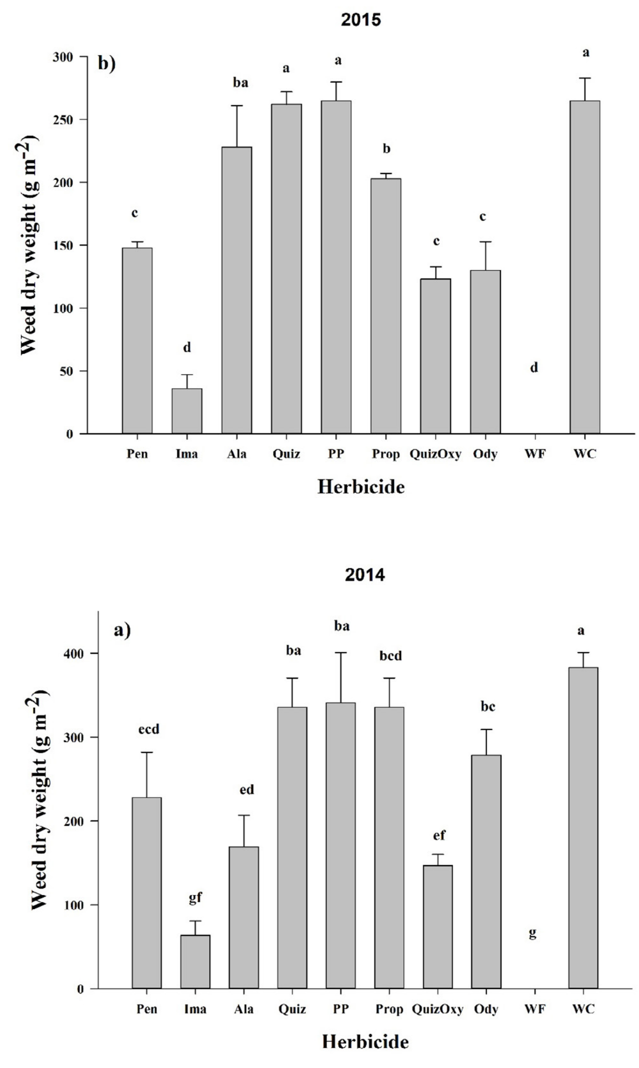

Fig 2. Total weed dry weight influenced by the herbicide application in fodder cowpea during 2014 (a) and 2015 (b) [Pen: pendimethalin; Ima: imazethapyr; Ala: alachlor; Quiz: quizalofop-p-ethyl; PP: tank imazethapyr + pendimethalin; Prop: propaquizafop; QuizOxy: tank mix quizalofop-p-ethyl and oxyflourfen; Ody: ready-mix imazamox + imazapyr; WF: weed free and WC: weedy control].

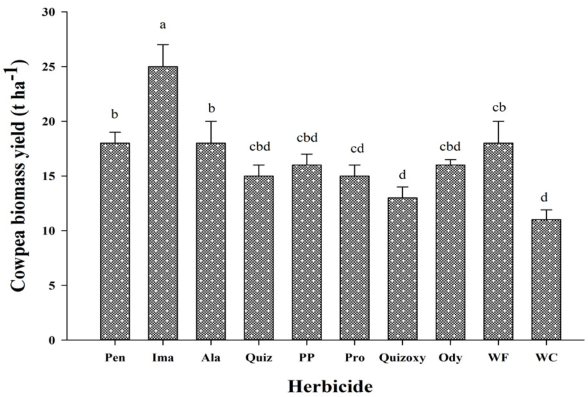

Fig 3. Cowpea green fodder yield influenced by different herbicide treatments

mix of atrazine + pendimethalin.This could be due to the broad-spectrum nature of herbicides and the application of pre-emergence and post-emergence herbicides with an interval of 17 to 20 days. For example, oxadiargyl has the ability to control grassy weeds, especially *Echinocloa colona*, and it has prolonged herbicidal activity in the soil, while 2,4-D is effective on broadleaved weeds (Rana *et al*., 2019). Therefore, this combination had a lower density and dry weight.A maximum green fodder yield was observed for the application of oxadiargyl, the tank mix of atrazine + pendimethalin, atrazine, and oxadiargyl - 2,4-D EE, compared to other herbicide treatments (Table 4).This could be attributed to better weed management throughout the crop growth phase, which may have resulted in higher sorghum green fodder yield. In comparison to the year 2014, 2015 had the lowest weed density and dry weight and the highest green fodder yield. This is because of the higher monthly rainfall in 2015 than in 2014 (Table 2). The higher rainfall might have enhanced the crop growth and competitive ability of crops over weeds, as well as the timely activation of soil-applied herbicides. For cowpea, the pre-emergence application of imazethapyr resulted in the lowest weed density and dry weight compared to other herbicide treatments in 2014 and 2015 (Figs 1a, b, 2a, and b). The next best treatments were the PRE-emergence application of pendimethalin and the POST-emergence application of ready-mix imazethapyr + imazamox. Imazethapyr treatment reduced weed density and dry weight by 83 to 86% compared to the unweeded control. The green fodder yield was comparable between imazethapyr and weed-free treatment (Fig 3). Imazethapyr produced more green fodder than other herbicide applications. Similarly, studies found that early post-application of imazethapyr, and ready mix pendimethalin + imazethapyr resulted in effective control of weeds in blackgram [*Vigna mungo* (L.) Hepper] (Verma *et al*., 2017). It indicates that early-season weed management is very critical for rainy-season crops like cowpeas. Once the cowpea crop gets established then they can easily suppress the weeds.

Integrated weed management for fodder cowpea and sorghum: Integrated weed management tactics had an effect ($p < 0.05$) on weed density, weed dry weight, and green fodder yield of sorghum (Table 6). However, the year and year-by-herbicide interaction did not influence the weed density, weed dry weight, and green fodder yield of sorghum ($p > 0.05$). Integration of one manual weeding after the PRE-application oxadiargyl decreased weed density (174.4 density m^{-2}) and weed dry weight (58.6 density m^{-2}) compared to PRE-application of oxadiargyl alone and unweeded control. As a result, a higher green fodder yield of fodder sorghum was obtained with the integration of one manual weeding after the PRE-application oxadiargyl. The increase in green fodder yield was 25.10% compared to the unweeded control. The results clearly demonstrate that effective weed management of upto 45 to 50 DAS of sorghum is important for higher yields (Thakur et al., 2016). Therefore, the combination of PRE-application of herbicide and one manual weeding resulted in lower weed density and dry weight, and higher yield. Similarly, an earlier study reported that the PRE-application of pendimethalin at 0.5 kg a.i ha^{-1}fb one-hand weeding at 30 DAS of sorghum effectively controlled weeds (65%

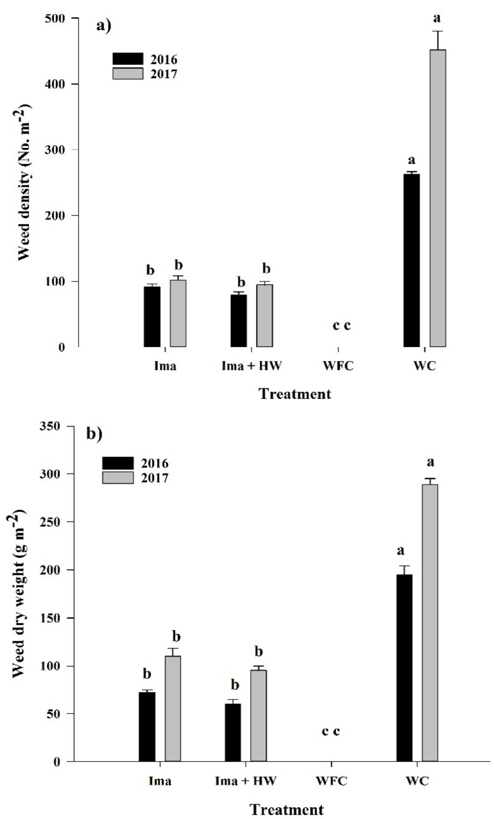

Fig 4. Weed density (a) and dry weight (b) influenced by integrated weed management tactics in fodder cowpea during 2016 and 2017 (Ima: imazethapyr; Ima + HW: imazethapyr and hand weeding; WFC: weed free control, and WC: weedy control)

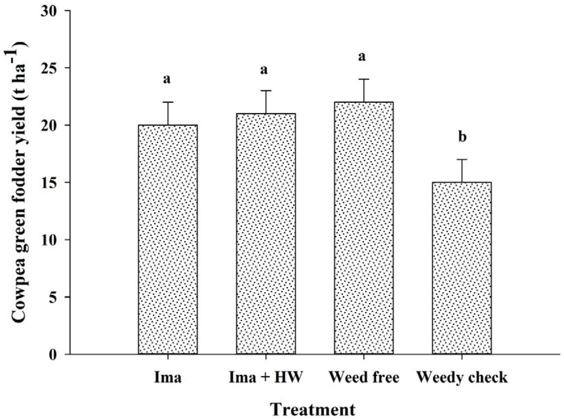

Fig 5. Cowpea biomass yield (b) influenced by integrated weed management tactics in fodder cowpea

control), and had higher net return (Rs 33548) in Madhya Pradesh, India (Sinchana and Raj, 2020).

The interaction effect of year-by-treatment was observed; therefore separate analysis was done for weed density and dry weight (Fig 4). In contrast, combined analysis was performed for the green fodder yield of cowpeas due to the non-significant effect of year-by-treatment. A two-year study revealed that the PRE-application of imazethapyr alone and PRE-application of imazethapyr followed by one-hand weeding resulted in the lowest total weed density and dry weight compared to unweeded control. The effective control of broad-spectrum weeds in the PRE-application of imazethapyr alone and PRE-application of imazethapyr followed by one-hand weeding led to a higher green fodder yield of cowpea (Fig 5). Fodder cowpea is genetically a fast-growing crop that requires a weed-free field at an early stage (Kumar and Singh, 2017). Results from our study also support the idea that early-stage weed management with PRE-application of imazethapyr or PRE-application of imazethapyr followed by one-hand weeding is essential for higher fodder yield. A previous study also indicated that the application of pendimethalin, followed by hand weeding and inter-cultural operations gave higher yields in cowpeas (Kumar and Singh, 2017).

Conclusion

Weed management is a key agronomic operation for any crop. Effective weed management practices could increase crop yield and improve produce quality by minimizing weed infestation. Two years of field research and one year of laboratory testing demonstrated that oxadiargyl can be a viable alternative herbicide to atrazine for fodder sorghum and imazethapyr for fodder cowpeas. Both the herbicides showed greater selectivity for crops and broad-spectrum activity on weeds. The two-year integrated weed management study also revealed that combining one manual weeding after the PRE-application of oxadiargyl and PRE-application of imazethapyr was effective in keeping the field weed-free and increased the green fodder yield of sorghum and cowpea, respectively. Furthermore, sorghum farmers still rely on atrazine. This herbicide is old and may be banned in the future. For that scenario, we found oxadiargyl as an alternative option for sorghum, which is a good herbicide showing selectivity to sorghum. However, it is not popular among farmers and scientists due to a lack of studies. This study would disseminate information about the use of oxadiargyl in fodder sorghum. For cowpeas, farmers rely on imazethapyr for both PRE and POST applications; no other recent herbicides are available for cowpeas. Future research on the integration of other cultural and mechanical approaches could preserve herbicides from the evolution of herbicide resistance.

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