INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
24–0172/2024/32–5–518–526
DOI: 10.17957/IJAB/15.2231
http://www.fspublishers.org

Full Length Article

Assessing Chemical Weed Control Strategies to Maximize Yield and Profitability of Pearl Millet Seed Crop

Naveed Akhtar[1], Ali Zohaib[2*], Tahira Tabassum[2], Hafiz Naveed Ramzan[3], Muhammad Idrees[4], Tasawer Abbas[5], Naeem Faisal[6], Faisal Shafiq[3], Muhammad Akram[4] and Muhammad Arif[4]

[1]*Vegetables and Oilseeds Section, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad 38850, Pakistan*

[2]*Cereals and Pulses Section, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad 38850, Pakistan*

[3]*Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad 38850, Pakistan*

[4]*Plant Physiology Section, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad 38850, Pakistan*

[5]*Department of Agronomy, University of Sargodha, Sargodha 40162, Pakistan*

[6]*Adaptive Research Farm, Gujranwala 52200, Pakistan*

[*]For correspondence: alizohaib208@gmail.com

Received 05 April 2024; Accepted 25 July 2024; Published 25 September 2024

Abstract

Heavy infestation of weeds in pearl millet seed crop curtails its seed yield and profitability. Chemical weed control in pearl millet at early growth stage with appropriate exclusive or pre-mixed herbicide and application timing is crucial for reducing yield losses and improve profitability. This two-year study including eight treatments was executed to ascertain different herbicides applied as pre-emergence (pendimethalin, atrazine, s-metolachlor and pre-mixed atrazine + s-metolachlor) and post-emergence (atrazine and pre-mixed atrazine + s-metolachlor) for effective weed control to improve growth, seed yield and profitability of pearl millet. Weed free and weedy check were used as controls. Atrazine (post-emergence) caused maximum decrease in weed density (98%) and weed dry biomass (93%) while increased weed control efficiency (WCE; 97%) and weed control index (WCI; 93%) which was comparable to weed free control. Likewise, this treatment resulted in the greatest increase in plant height (8%), leaf area (65%), stem thickness (10%), tillers plant^{-1} (6.22; 165%), seed weight (13.0 g; 41%), seed yield (1.73 t ha^{-1}; 140%) and benefit:cost ratio (BCR; 2.55) and these results were followed by pre-mixed atrazine + s-metolachlor (post-emergence). A significant negative relationship of weed density with seed yield and WCE with yield loss indicates that reducing weed density through effective weed control practices can minimize yield loss. In conclusion, atrazine (post-emergence) increased seed yield and profitability of pearl millet by effective weed control and decreased yield loss; hence, it could be employed for enhancing seed production. However, pre-mixed atrazine + s-metolachlor (post-emergence) could be utilized as an alternative.

Keywords: Economic benefits; Herbicides; Pearl millet; Regression analysis; Weed control efficiency; Yield loss

Introduction

Pearl millet (*Pennisetum glaucum* L.) is one of the essential fodder crops as feed for livestock due to good palatability (Yusuf *et al.* 2012). It is gaining prominence as fodder crop in many regions of the world due to its high nutritional value i.e. dry matter content (36–39%), crude protein (6–8%), crude fiber (25–29%), ash (7–16%) and ether extract (3%) (Yusuf *et al.* 2012; Rasool *et al.* 2017). It is an abiotic stress-tolerant crop, predominantly cultivated in marginal environments found in arid and semi-arid tropics of the Asia and Africa (Satyavathi *et al.* 2021). It is a dual purpose (fodder and grain), quick growing and short duration crop having better salinity and drought tolerance characteristics (Vadez *et al.* 2012; Kumawat *et al.* 2016; Kheya *et al.* 2023). Lower yield of the fodder crops is primarily associated with scarcity of proper area under forage crops and lack of good quality seed (Yusuf *et al.* 2012; Rasool *et al.* 2017).

Pearl millet is severely infested by weeds which curtail the yield and economics of crops in respect of seed production. The presence of weed flora affects the yield and quality of the seed. Weeds cause 27–36% loss in the seed yield of pearl millet (Carson 2008). Therefore, it is very important to control the weeds in pearl millet for enhancement of seed yield and in turn improve the fodder

To cite this paper: Akhtar N, A Zohaib, T Tabassum, HN Ramzan, M Idrees, T Abbas, N Faisal, F Shafiq, M Akram, M Arif (2024). Assessing chemical weed control strategies to maximize yield and profitability of pearl millet seed crop. *Intl J Agric Biol* 32:518–526

yield (Nourou *et al.* 2020). Proper weed management has substantial positive impact on seed production of pearl millet (Arslan *et al.* 2018; Mohammad *et al.* 2021). Previous research has shown that reduction in weed density by different weed management practices resulted in improvement in plant growth, grain and fodder yield, and economics of pearl millet (Arslan *et al.* 2018; Bhuva and Detroja 2018). However, the problem of weeds in pearl millet seed crop is severe due to lack of appropriate weed control method.

Chemical weed control strategies could be employed for managing the weeds and improving seed production of pearl millet crop (Cuerrier *et al.* 2010; Pawar *et al.* 2021). Previous research has demonstrated that chemical weed control methods reduced the weed density and improved the yield of pearl millet (Mohammad *et al.* 2021). Weeds pose a substantial threat to the growth and yield of crop plants during early growth stage; therefore, it is imperative to promptly eradicate the weeds during early stages of crop development (Wasnik *et al.* 2017; Kaur *et al.* 2020). Pendimethalin (cell division inhibitor) and s-metolachlor (long chain fatty acid inhibitor) are predominantly used as pre-emergence herbicides in various crops to control the weeds during early growth stage of crops (Vighi *et al.* 2017; Chen *et al.* 2021; Rangani *et al.* 2021). Atrazine (photosynthesis inhibitor) herbicide could be used either as pre- or post-emergence to eradicate narrow and broad-leaved weeds (Bhuva and Detroja 2018; Chaudhary *et al.* 2022).

Atrazine has great agronomic importance for selective control of diverse weeds in crops such as maize, sorghum and pearl millet (Bhuva and Detroja 2018; Sousa *et al.* 2022). However, the continuous use of the same herbicide may influence the weed control efficiency and lead to development of herbicide resistant weeds (Powles and Yu 2010). Application of s-metolachlor as pre-emergence herbicide provides broad spectrum weed control in many crops (Zemolin *et al.* 2014) but it has been reported that it caused injury to pearl millet crop (Cuerrier *et al.* 2010). Pendimethalin could be alternatively used as pre-emergence herbicide for weed control in pearl millet because of its safety to crop plants but its effect on seed yield is inconsistent (Cuerrier *et al.* 2010; Kiroriwal *et al.* 2012; Pawar *et al.* 2021). Additionally, application of herbicides as mixture could be more useful in reducing the weed density and minimizing the risk of developing herbicide resistant weeds and environmental pollution due to reduced amount of active ingredients (Cioni and Maines 2010; Kumar *et al.* 2012). Besides, optimization of application time of herbicides aligns their use well with their characteristics, environmental conditions and life cycle of weeds thereby maximizing their effectiveness (Grzanka *et al.* 2022).

Weed infestation in pearl millet causes enormous loss in the growth and yield of seed crop. Chemical weed control stands out to be an effective strategy for managing weeds in pearl millet (Pawar *et al.* 2021; Chaudhary *et al.* 2022). However, information regarding effective exclusive and pre-mixed herbicides and their optimal application timing for weed management and yield of pearl millet seed crop is deficient. Additionally, the relationship of weed flora and weed control efficiency with yield loss of pearl millet is not well-understood and requires further investigation. In this study, it was hypothesized that if appropriate exclusive or pre-mixed herbicide is applied at optimum time then it will improve weed control efficiency and decrease yield loss of pearl millet seed crop. The current research aimed to (a) assess the effectiveness of different exclusive or pre-mixed herbicides applied either as pre-emergence or post-emergence on weed management, plant growth, seed yield and profitability of pearl millet seed crop and (b) find out the relationship of weed density and weed control efficiency with seed yield and yield loss of pearl millet, respectively, in response to herbicide treatments.

Materials and Methods

Evaluation of different herbicides for weed control, seed yield and profitability of pearl millet seed crop was carried out at Cereals and Pulses Research Area, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad (31º24′03″N latitude 73º04′09″E longitude and 185 m above sea level) during 2018 and 2019. Prior to sowing the crop at experimental area, soil samples were collected and analyzed to ascertain the soil physico-chemical properties. The soil was loam having electrical conductivity (EC) 0.77 mS cm^{-1}, pH 7.8, organic matter 0.69%, total nitrogen content 0.049%, available phosphorus 7.3 mg kg^{-1} and available potash 165 mg kg^{-1}. The study was conducted by laying out the experiment in randomized complete block design and replicating thrice. The plot area was 10 m × 3 m. The meteorological conditions encountered throughout the crop growing seasons during 2018 and 2019 are depicted in Table 1.

Treatment details

Treatments included application of diverse herbicides as pre- or post-emergence (Table 2). Weed free and weedy check plots were taken as control. Weed-free plots underwent complete weed eradication by hoeing and/or hand weeding throughout the crop growing season, whereas weeds were left unattended in the weedy check plots (Table 2). Herbicides were applied as pre-emergence (pendimethalin, atrazine, s-metolachlor and pre-mixed atrazine + s-metolachlor) and post-emergence (atrazine and pre-mixed atrazine + s-metolachlor) at specified rates (Table 2). Pre-emergence herbicides were applied immediately after sowing the crop. Post-emergence herbicides were applied 25 days after sowing (DAS) (Table 2). Herbicides were sprayed using a knapsack sprayer utilizing 300 L ha^{-1} of water at a pressure of 207 kPa.

Table 1: Meteorological conditions during pearl millet growing seasons

Month	Temperature (°C)						Total rainfall (mm)		Relative humidity (%)	
	Monthly maximum		Monthly minimum		Daily mean					
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
July	37.0	37.0	27.7	26.7	32.3	31.8	195.8	164.6	70.2	66.1
August	39.0	37.2	29.5	26.9	34.2	32.0	58.4	84.0	67.4	68.6
September	37.2	36.9	25.2	26.4	31.4	31.6	41.7	48.1	65.1	66.0
October	32.6	32.9	18.7	18.9	25.6	25.9	15.0	22.4	64.4	64.6
November	27.0	26.3	12.4	12.8	19.7	19.6	0.6	3.0	74.6	77.0

Source: Plant Physiology Section, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad

Table 2: Treatment details of the experiment (2018 and 2019)

Treatments	Description
Pendimethalin	Applied as pre-emergence at the dose of 1.24 kg a.i. ha^{-1} immediately after sowing of the crop
Atrazine	Applied as pre-emergence at the dose of 0.48 kg a.i. ha^{-1} immediately after sowing of the crop
S-metolachlor	Applied as pre-emergence at the dose of 1.92 kg a.i. ha^{-1} immediately after sowing of the crop
Pre-mixed atrazine + s-metolachlor	Applied as pre-emergence at the dose of 0.32 kg a.i. ha^{-1} atrazine + 0.40 kg a.i. ha^{-1} s-metolachlor immediately after sowing of the crop
Atrazine	Applied as post-emergence at the dose of 0.48 kg a.i. ha^{-1} 25 DAS
Pre-mixed atrazine + s-metolachlor	Applied as post-emergence at the dose of 0.32 kg a.i. ha^{-1} atrazine + 0.40 kg a.i. ha^{-1} s-metolachlor 25 DAS
Weed free control	Weeds were removed by hoeing and/or hand weeding throughout the experimental period
Weedy check control	No weed control measure was practiced throughout the experimental period

Crop husbandry

Pearl millet variety Sargodha Bajra-2011 was used for the experiment. The crop was sown on 15th and 18th July during 2018 and 2019, respectively. Sowing of pearl millet on 30 cm apart lines was carried out using 7.5 kg ha^{-1} seed rate. Fertilization of crop was carried out at a dose of 50-57-31 kg NPK ha^{-1} utilizing the urea, diammonium phosphate (DAP) and sulphate of potash (SOP), respectively. The entire doses of DAP and SOP were administered during sowing, whereas urea was applied at the jointing stage. The crop was irrigated 3–4 times during both years depending upon the soil and weather conditions. Insect pest and disease management was carried out following recommended practices. Crop was harvested manually for data collection at maturity.

Observations

Major weed species present in the experimental field were observed and are given in Table 3. Weed density (weeds m^{-2}) was determined by counting the weeds m^{-2} from each replication 35 DAS and then averaged. Weed dry biomass was determined by drying the uprooted weeds in oven at 70 ± 5ºC until constant weight from each replication. The WCE, percent decrease in weed density by weed control treatments, was calculated according to Kaur *et al.* (2020);

$$WCE\ (\%) = \left[\frac{(WPD_c - WPD_t)}{WPD_c} \times 100\right]$$

Where, WPD_C and WPD_T denote the weed plant density m^{-2} of un-weeded control and respective weed control treatment, respectively.

The WCI, percent decrease in the weed dry biomass by a weed control treatment, was calculated according to Kaur *et al.* (2020);

$$WCI\ (\%) = \left[\frac{(WDB_c - WDB_t)}{WDB_c} \times 100\right]$$

Where, WDB_c and WDB_t denote the weed dry biomass m^{-2} of weed free control and respective treatment plots, respectively.

Plant growth, seed yield and related attributes

Pearl millet emergence (plants m^{-2}) was recorded 12 DAS. Plant height measurement was made using a measuring rod by randomly selecting the five plants from each replication at maturity and then averaged. The leaf area of selected plants was recorded using graphical method at 60 DAS and employing the formula (length × width × 0.75), and then averaged. Stem thickness of selected five plants was recorded using a vernier caliper at maturity and averaged. The number of tillers plant^{-1} was determined by counting the tillers of five selected plants at maturity and averaged. Head length was appraised at maturity using a measuring rod and the measurements were averaged. The 1000-seed weight was recorded by counting and weighing with electric weighing balance. Pearl millet was harvested at maturity and threshed manually for the determination of seed yield and expressed as t ha^{-1}.

Yield loss due to weed infestation across the treatments was computed according to the Dodamani and Das (2013);

$$Yield\ loss\ (\%) = \left[\frac{(Y_{wf} - Y_t)}{Y_{wf}} \times 100\right]$$

Where, Y_{wf} and Y_t denote the seed yield of weed free control and respective treatment plots, respectively.

Economic analysis

Benefit:cost ratio, net returns and total cost was

Table 3: Major weed species present in the experimental field

Botanical name	Common name	Family	Habit and characteristics
Trianthema portulacastrum	Horsepurslane	Aizoaceae	Annual broadleaved herb
Digera arvensis	False amaranth	Amaranthaceae	Annual broadleaved herb
Dactyloctenium aegyptium	Crowfoot grass	Poaceae	Annual grass herb
Echinochloa colona	Barnyard grass	Poaceae	Annual grass herb
Sorghum halepense	Johnsongrass	Poaceae	Perennial grass herb
Cyperus rotundus	Purple nut sedge	Cyperaceae	Perennial sedge herb

computed in accordance with the methodology outlined by CIMMYT (1988). Fixed and variable costs and gross income were computed with market prices of all used inputs and produce, respectively. Total cost was calculated by adding together both fixed and variable costs. Seed yield was multiplied with the market price to calculate the gross income. Total cost was deducted from gross income to compute the net returns. Benefit:cost ratio was determined as follows; [BCR = (gross income/total cost)].

Statistical analysis

Data related to weed density; plant growth, yield and related traits of pearl millet were square root transformed before carrying out further analyses. However, no difference was found in significance test between non-transformed and transformed data; hence, non-transformed original data of weeds as well as pearl millet was used for further analyses. Almost similar temperature, rainfall and relative humidity existed during 2018 and 2019 (Table 1) due to which non-significant difference between years (year effect) existed according to paired T-test; therefore, data were presented after averaging the data of both years. The statistical analyses of data were done using Fisher's analysis of variance technique (Steel *et al.* 1997). Significance of differences between treatments' means was determined by utilizing the least significant difference (LSD) test at 5% level of significance. Linear regression analyses were performed to determine the relationship of weed density and weed dry biomass with seed yield and WCE and WCI with yield loss.

Results

Chemical weed management significantly affected the weed density, weed dry biomass, WCE and WCI (Table 4; Fig. 1). The least weed density and weed dry biomass, and highest WCE and WCI were exhibited by weed free control (Table 4; Fig. 1). Application of herbicides as post-emergence was more effective in decreasing the weed density and dry biomass while improving the WCE and WCI in comparison to application as pre-emergence (Table 4). Among herbicides, the highest decrease in weed density (98%) and weed dry biomass (93%) was caused by atrazine (post-emergence), in comparison to weedy check control and these results were followed by pre-mixed atrazine + s-metolachlor (post-emergence) (Table 4; Fig. 1). Nonetheless, atrazine applied as post-emergence resulted in the highest upsurge in WCE (97%) and WCI (93%), and it was followed by pre-mixed atrazine + s-metolachlor (post-emergence) (Table 4; Fig. 1). However, minimum decline in weed density (53%) and weed dry biomass (43) while increase in WCE (53%) and WCI (42%) was caused by pendimethalin (pre-emergence), as compared to weedy check control, among different herbicide treatments (Table 4; Fig. 1).

Emergence, plant growth, seed yield and related attributes and yield loss of pearl millet were significantly affected by chemical weed control (Table 4). Weed free control exhibited the greatest plant height, leaf area, stem thickness, head length, number of tillers plant^{-1}, 1000-seed weight and seed yield while minimum yield loss of pearl millet while vice versa was recorded by weedy check control (Table 4). Emergence of pearl millet was reduced by application of pre-emergence herbicides and the highest reduction was caused by s-metolachlor (Table 4). Plant growth, seed yield and related attributes of pearl millet were enhanced more by the application of herbicides as post-emergence as compared to application as pre-emergence (Table 4). Furthermore, minimum yield loss was also recorded by herbicides applied as pre-emergence in comparison to post-emergence (Fig. 2). Atrazine (post-emergence) caused maximum increase in plant height (8%), leaf area (65%), stem thickness (10%), head length (176%), number of tillers plant^{-1} (165%), 1000-seed weight (41%) and seed yield (140%) of pearl millet in comparison to weedy check control and the pre-mixed atrazine + s-metolachlor (post-emergence) showed the similar trend regarding these results (Table 4; Fig. 2). Similarly, the greatest reduction in yield loss (13%) of pearl millet was recorded by the atrazine (post-emergence), as compared to weedy check control (Fig. 2). However, minimum increase in plant growth (2–5%), seed yield (44%) and yield related attributes (6–30%) and reduction in yield loss (47%) was caused by pendimethalin (pre-emergence), as compared to weedy check control, among different herbicide treatments (Table 4; Fig. 2).

A significant negative linear relationship of seed yield existed with weed density (R^2 0.7816) and weed dry biomass (R^2 0.8015) (Fig. 3). Similarly, significant negative linear relationship of yield loss was observed with WCE (R^2 0.8114) and WCI (R^2 0.8292) (Fig. 3).

Economic analysis revealed that chemical weed control treatments enhanced the economic returns and BCR of pearl millet, as compared to un-weeded control (Table 5). After weeds free control, application of pendimethalin (pre-

Table 4: Effect of different herbicides on weed density, plant growth and yield related traits of pearl millet

Treatment	Weed density m^{-2}	Weed dry biomass (g m^{-2})	Emergence of pearl millet (plants m^{-2})	Plant height (cm)	Leaf area (cm^2)	Stem thickness (cm)	Head length (cm)	No. of tillers $plant^{-1}$	1000-seed weight (g)
Pendimethalin (pre-emergence)	46.20 b	6.49 b	31.7 ab	259.0 fg	175.2 g	1.32 f	14.69 g	2.53 fg	9.00 de
Atrazine (pre-emergence)	18.20 e	2.79 d	30.3 abc	269.1 cd	233.8 d	1.38 cd	24.50 d	4.15 cd	10.50 bcd
S-metolachlor (pre-emergence)	36.80 c	4.59 c	28.0 c	262.0 ef	185.9 f	1.34 ef	17.90 f	3.00 ef	9.50 cde
Pre-mixed atrazine + s-metolachlor (pre-emergence)	30.40 d	3.34 d	29.0 bc	266.2 de	203.5 e	1.36 de	21.20 e	3.51 de	10.00 cde
Atrazine (post emergence)	2.40 g	0.78 f	32.3 ab	275.0 b	275.0 b	1.42 b	31.20 b	5.30 b	12.00 ab
Pre-mixed atrazine + s-metolachlor (post-emergence)	13.20 f	1.86 e	33.7 a	272.7 bc	249.3 c	1.40 bc	27.78 c	4.50 bc	11.00 bc
Weed free control	0.00 h	0.00 g	32.0 ab	280.9 a	283.6 a	1.45 a	35.13 a	6.22 a	13.00 a
Weedy check control	97.80 a	11.31 a	33.0 a	255.1 g	167.1 h	1.29 g	11.30 h	2.00 g	8.50 e
LSD ($P \leq 0.05$)	2.188	0.731	3.603	4.397	4.469	0.029	1.275	0.971	1.732

Means in a column followed by different letters are significantly different at $P \leq 0.05$ as per LSD values

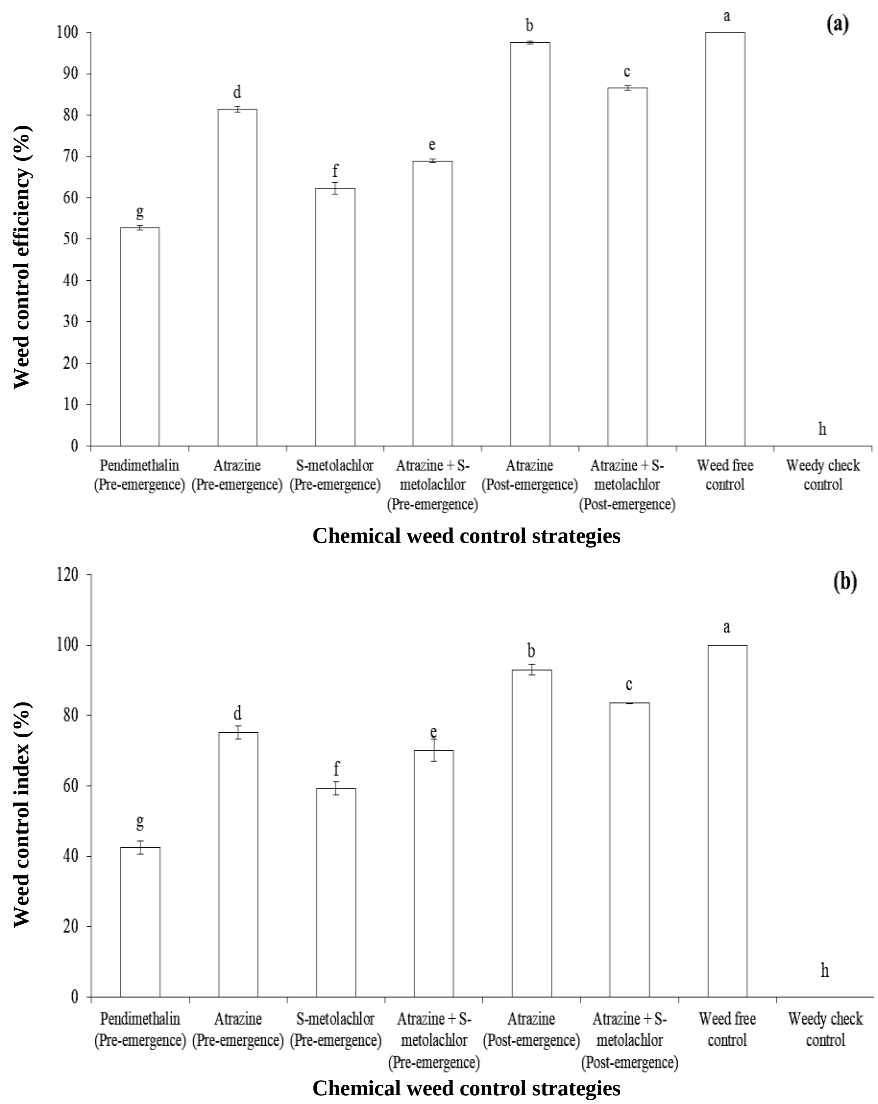

Fig. 1: Effect of different herbicides on (**a**) weed control efficiency (%) and (**b**) weed control index (%) in pearl millet. Bars are mean ± SE of three replications. Bars sharing the different letters differ significantly at $P \leq 0.05$

emergence) was the most expensive while atrazine (pre- or post-emergence) was the least expensive and it was followed by pre-mixed atrazine + s-metolachlor (pre- or post-emergence) (Table 5). However, except weed free control, maximum gross income (Rs. 82950) and net benefits (Rs. 50409) were obtained by application of atrazine (post-emergence), and these results were followed by pre-mixed atrazine + s-metolachlor (post-emergence)

Table 5: Effect of different herbicides on profitability of pearl millet

Treatments	Adjusted seed yield (kg ha^{-1})	Gross income (Rs. ha^{-1})	Fixed cost (Rs. ha^{-1})	Variable cost (Rs. ha^{-1})	Total cost (Rs. ha^{-1})	Net benefits (Rs. ha^{-1})	BCR
Pendimethalin (pre-emergence)	819	55950	31229	4688	35917	20033	1.56
Atrazine (pre-emergence)	1044	67200	31229	1312	32541	34659	2.07
S-metolachlor (pre-emergence)	891	59550	31229	3025	34254	25296	1.74
Pre-mixed atrazine + s-metolachlor (pre-emergence)	981	64050	31229	1575	32804	31246	1.95
Atrazine (post emergence)	1359	82950	31229	1312	32541	50409	2.55
Pre-mixed atrazine + s-metolachlor (post-emergence)	1215	75750	31229	1575	32804	42946	2.31
Weed free control	1557	92850	31229	9840	41069	51781	2.26
Weedy check control	567	43350	31229	0	31229	12121	1.39

Average adjusted seed yield = 10% less than actual seed yield averaged over two years (2017 and 2018)

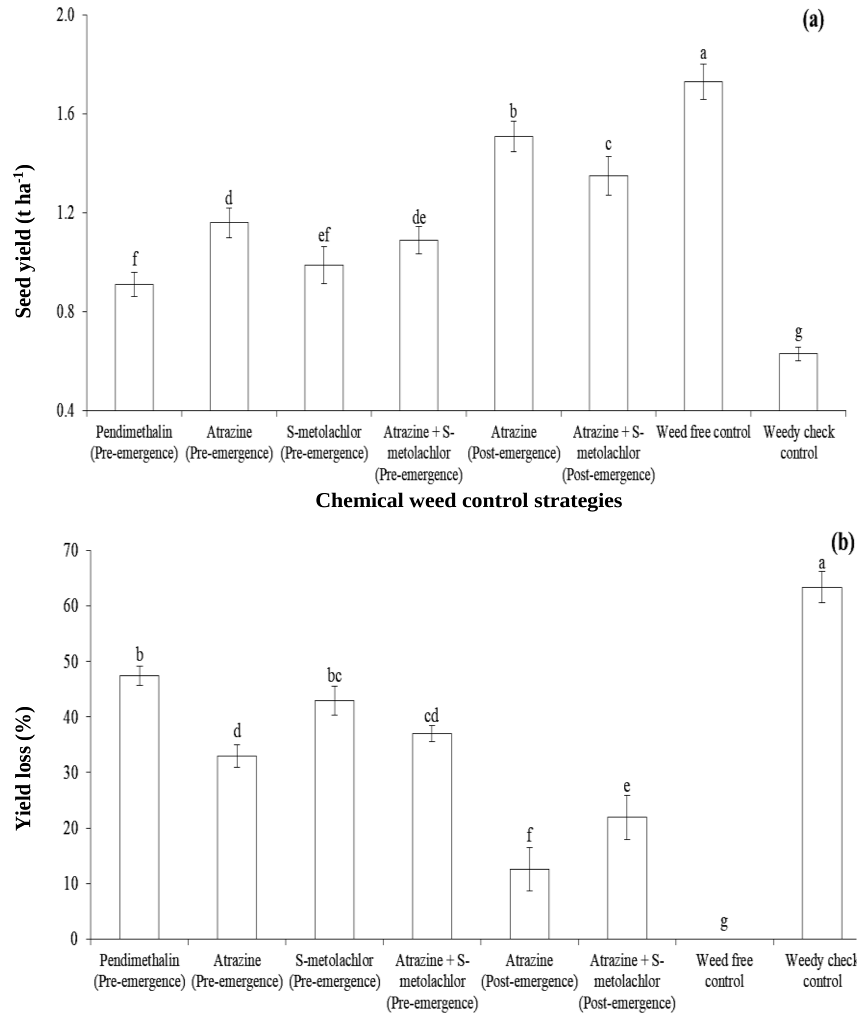

Fig. 2: Effect of different herbicides on (**a**) seed yield and (**b**) yield loss of pearl millet. Bars are mean ± SE of three replications. Bars sharing the different letters differ significantly at $P \leq 0.05$

(Table 5). However, maximum BCR (2.55) was recorded by atrazine (post-emergence) and it was followed by pre-mixed atrazine + s-metolachlor (post-emergence) even more than weed free control (Table 5).

Discussion

In present study, weed density and weed dry biomass were decreased while WCE and WCI were increased by chemical

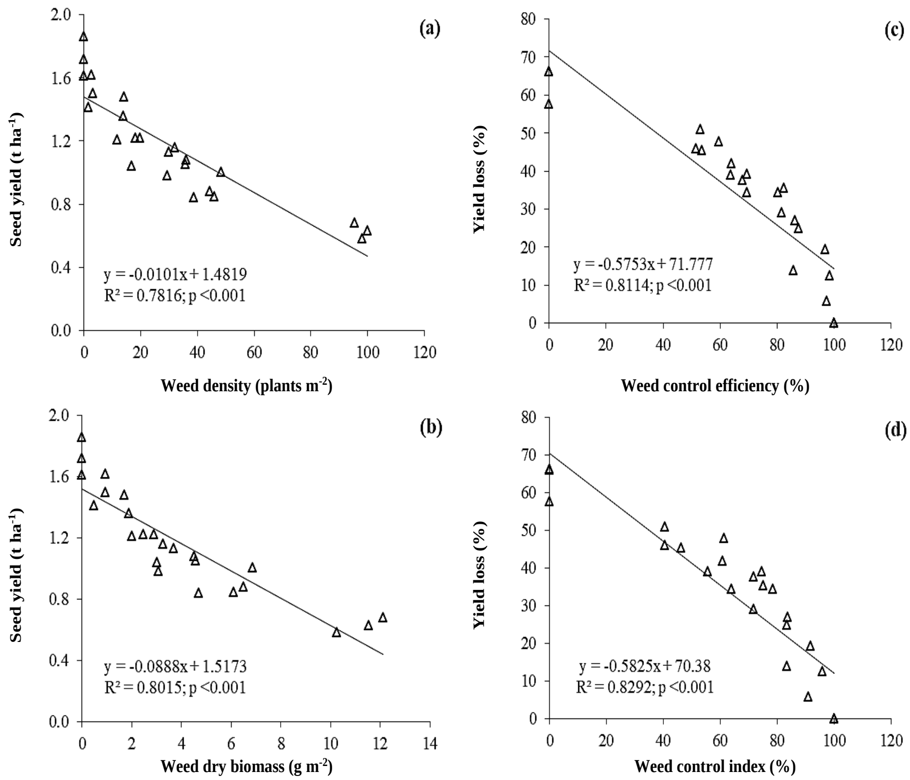

Fig. 3: Relationship between (**a**) weed density (plants m^{-2}) and seed yield (t ha^{-1}), (**b**) weed dry biomass (g m^{-2}) and seed yield (t ha^{-1}) (**c**) weed control efficiency (%) and yield loss (%) and (**d**) weed control index (%) and yield loss (%). Coefficients of determination (R^2), significance of coefficients ($P < 0.05$) and dependence of seed yield (y) on (a) weed density (x) and (b) weed dry biomass (x), and yield loss (y) on weed control efficiency (x) and weed control index (x) are given (n = 24)

weed control either by application as pre- or post-emergence herbicides, in comparison to weedy check control (Table 4; Fig. 1). Moreover, atrazine and/or pre-mixed atrazine + s-metolachlor applied as post-emergence more effectively controlled the weeds than application of pre-emergence herbicides (Table 4; Fig. 1). Less weed density and better WCE in response to atrazine applied as post-emergence could be attributed to its persistence for longer period (Banga *et al.* 2000; Ram *et al.* 2005; Mitra *et al.* 2018) as it is also apparent from the effectiveness of atrazine in controlling weeds when applied as pre-emergence in comparison to other pre-emergence herbicides (Table 4; Fig. 1). The findings of our study align with those of Bhuva and Detroja (2018) as well as Chaudhary *et al*. (2022) who described that application of atrazine as post-emergence herbicide effectively controlled the weeds and exhibited lower weed density in comparison to weedy check control. However, Munde *et al*. (2012) observed that atrazine treatment more effectively controlled the broadleaf weeds than narrow leaf weeds in pearl millet and recorded less weed density than weedy check control.

In the present study, pre-emergence application of pendimethalin did not reduce emergence of pearl millet (Table 4). Minimum injury to emerging seedlings might be due to its selectivity which is associated with positioning of crop and weed seeds placed within soil because it is absorbed by roots rather than shoots (Chen *et al.* 2021). Previous research has also demonstrated that pendimethalin did not cause injury to emerging seedlings of pearl millet (Cuerrier *et al.* 2010). In this study, pre- and post-emergence application of atrazine in sole and mixture formulations caused the least injury at early emergence stage (Table 4). This could be attributed to better selectivity of atrazine for pearl millet and weeds (Bhuva and Detroja 2018). Previous research has demonstrated that low concentrations of atrazine did not affect the emergence of different crops (Chowdhury *et al.* 2020). In the present study, pre-emergence application of s-metolachlor either alone or pre-mixed with atrazine reduced emergence of pearl millet (Table 4). The persistence and bioactivity of s-metolachlor in soil is associated with organic matter, temperature and microbial activity (Zemolin *et al.* 2014). In the present study, soil was deficient in organic matter (0.69%) which might have increased its persistence and toxicity thereby reducing emergence (Table 4). Cuerrier *et al.* (2010) also reported similar effects of s-metolachlor on emergence of pearl millet.

In the present study, weed-crop competition for available resources resulted in decreased plant growth of pearl millet and increase in weed density caused a drastic reduction due to high weed-crop competition (Table 4). These results are in confirmation with Dhage *et al*. (2008) and Mathukia *et al*. (2015). However, in this study, chemical weed control reduced the weed-crop competition by suppression of weeds which led to an increase in plant height, leaf area and stem thickness of pearl millet (Table 4). Similarly, Singh *et al*. (2017) and Arslan *et al.* (2018) described that decrease in weed density by proper weed control practices resulted in significant increase in plant height and stem thickness. In present study, pendimethalin (pre-emergence) exhibited decreased plant growth of pearl millet which was associated with more weed-crop competition rather than crop injury (Table 4). However, pre-emergence application of s-metolachlor either sole or pre-mixed with atrazine caused reduction in crop growth which is attributed to crop injury due to its high persistence in soil and toxicity instead of weed-crop competition (Cuerrier *et al.* 2010; Zemolin *et al.* 2014). Application of atrazine alone or pre-mixed with s-metolachlor especially as post-emergence did not cause injury to pearl millet resulting in improved growth which may be attributed to its better selectivity towards pearl millet at normal dose (Dan *et al.* 2010).

Chemical weed control treatments caused a notable decrease in yield loss of pearl millet as depicted by negative relationship of WCE with yield loss (Fig. 2 and 3). This reduced yield loss by chemical weed control is attributed to reduced weed-crop competition which resulted in increased number of tillers plant^{-1}, head length and 1000-grain weight (Table 4). Previous studies have demonstrated that effective weed control by application of pre- and post-emergence herbicides reduced the weed-crop competition ultimately increasing crop yield (Ram *et al.* 2004; Mathukia *et al.* 2015; Dhayal *et al.* 2020). In present study, post-emergence application of atrazine as exclusive or pre-mixed with s-metolachlor caused maximum increase in seed yield and related attributes and decrease in yield loss (Table 4; Fig. 2) which was associated with better WCE and least crop injury (Table 4; Fig. 1; Dan *et al.* 2010; Chowdhury *et al.* 2020). Similarly, Bhuva and Detroja (2018) observed that atrazine (applied as post-emergence) most effectively improved the tillers plant^{-1}, head length, 1000-seed weight and seed yield of pearl millet.

Profitability of pearl millet seed crop was enhanced by chemical weed control in comparison to weedy check control (Table 5). Among different herbicides, the greatest increase in net benefits and BCR was caused by atrazine (post-emergence) and it was followed by pre-mixed atrazine + s-metolachlor (post-emergence) (Table 5). The greatest improvement in profits and BCR by atrazine (post-emergence) is attributed to its low cost and better weed management and seed yield of pearl millet (Table 4; Fig. 2). Various studies have demonstrated that similar to present study better weed management in crops improved the profitability and BCR (Singh *et al.* 2011; Mishra *et al.* 2015; Chinyo *et al.* 2023).

Conclusion

Application of all herbicides caused a reduction in weed-crop competition by reducing the weed density and biomass with enhanced WCE which resulted in improved plant growth, seed yield and profitability of pearl millet. However, among various herbicides, the atrazine applied as post-emergence demonstrated the highest decline in weed density and improvement in WCE which enhanced the seed yield and profitability of pearl millet. Hence, post-emergence application of atrazine could be adopted for better weed control and seed production. However, pre-mixed atrazine + s-metolachlor (applied as post-emergence) offer a suitable alternative to sole application of atrazine.

Acknowledgements

Authors thank the Agriculture Department (Research wing), Govt. of the Punjab, Pakistan for providing the support and funding, and all the collaborators who contributed to execute this work.

Author Contributions

NA, planning and supervision of experimentation, AZ, data analysis, creation of illustrations, results interpretation and paper write-up, TT and HNR, help in literature review, MI, help in economic analysis, TA and NF, review and editing, FS, help in data analysis, MA and MA, help in methodology.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics Approval

Not applicable to this paper.

References

Arslan N, U Zulfiqar, M Ishfaq, M Ahmad, MN Anwar, A Ullah, I Nazar, A Iqbal, MZ Anjum (2018). Weed control practices and varying sowing dates affect seed production of pearl millet (*Pennisetum americanum* L) under semi-arid environment. *Amer J Plant Sci* 9:1974–1986

Banga RS, A Yadav, RK Malik, SK Pahwa, RS Malik (2000). Evaluation of tank mixture of acetachlor and atrazine or 2, 4-D Na against weeds in pearl millet. *Ind J Weed Sci* 32:194–198

Bhuva HM, AC Detroja (2018). Pre-and post-emergence application of atrazine in integration with hand weeding for weed management in pearl millet. *Ind J Weed Sci* 50:273–277

Carson AG (2008). Improving weed management in the draft animal-based production of early pearl millet in the Gambia. *Intl J Pest Manage* 33:359–363

Chaudhary C, VS Hooda, Isha, M Nagora, S Kumar, DP Nandal (2022). Impact of integrated weed management practices on weed parameters and yield of pearl millet (*Pennisetum glaucum* L. Br. Emend Stuntz). *Pharm Innov J* 11:693–700

Chen J, Q Yu, E Patterson, C Sayer, S Powles (2021). Dinitroaniline herbicide resistance and mechanisms in weeds. *Front Plant Sci* 12:634018

Chinyo M, R Singh, M Gautam (2023). Weed management with pre-and post-emergence herbicide in rainfed pearl millet under conservation agriculture. *Ind J Weed Sci* 55:223–227

Chowdhury IF, GS Doran, BJ Stodart, C Chen, H Wu (2020). Trifluralin and atrazine sensitivity to selected cereal and legume crops. *Agronomy* 10:587

CIMMYT (1988). *From Agronomic Data to Farmers Recommendations: An Economics Training Manual*. Completely revised edition. Mexico City, Mexico

Cioni F, G Maines (2010). Weed control in sugarbeet. *Sugar Tech* 12:243–255

Cuerrier ME, A Vanasse, GD Leroux (2010). Chemical and mechanical weed management strategies for grain pearl millet and forage pearl millet. *Can J Plant Sci* 90:371–381

Dan HA, ALL Barroso, SO Procópio, LGM Dan, TR Finotti, RL Assis (2010). Atrazine selectivity in pearl millet (*Pennisetum glaucum*). *Plant Danin* 28:1117–1124

Dhage VJ, BT Shete, JB Patil (2008). Effect of integrated weed management on growth attributes of pearl millet-pigeonpea intercropping system. *Annu Rev Plant Physiol* 22:183–185

Dhayal BC, SS Yadav, ML Jat, L Dhayal (2020). Efficacy of herbicides for weed control in pearl millet (*Pennisetum glaucum* (L.) R. Br. Emend Stuntz). *Environ Ecol* 38:651–656

Dodamani BM, TK Das (2013). Density and nitrogen effects on interference and economic threshold of common lambsquarters in wheat. *J Pest Sci* 86:611–619

Grzanka M, L Sobiech, R Idziak, G Skrzypczak (2022). Effect of the time of herbicide application and the properties of the spray solution on the efficacy of weed control in maize (*Zea mays* L.) cultivation. *Agriculture* 12:353

Kaur R, TK Das, T Banerjee, R Raj, R Singh, S Sen (2020). Impacts of sequential herbicides and residue mulching on weeds and productivity and profitability of vegetable pea in North-western Indo-Gangetic Plains. *Sci Hortic* 270:109456

Kheya SA, SK Talukder, P Datta, S Yeasmin, MH Rashid, AK Hasan, MP Anwar, AKMA Islam, AKMM Islam (2023). Millets: The future crops for the tropics-status, challenges and future prospects. *Heliyon* 9:e2213

Kiroriwal A, RS Yadav, A Kumawat (2012). Weed management in pearlmillet based intercropping system. *Ind J Weed Sci* 44:200–203

Kumar S, R Singh, R Shyan, VK Singh (2012). Weed dynamics, nutrients removal and yield of wheat as influenced by weed management practices under valley conditions of Uttarakhand. *Ind J Weed Sci* 44:110–114

Kumawat SM, M Arif, SS Shekhawat, SR Kantwa (2016). Effect of nitrogen and cutting management on growth, yield and quality of fodder pearl millet (*Pennisetum glaucum* L) cultivars. *Range Manage Agrofor* 37:207–213

Mathukia RK, PR Mathukia, AM Polara (2015). Intercropping and weed management in pearl millet (*Pennisetum glaucum*) under rainfed condition. *Agric Sci Digest* 35:138–141

Mishra SP, YR Ramu, D Subramanyam, V Umamahesh, RR Manoja, GP Reddy (2015). Weed dynamics, yield and economics of pearl millet (*Pennisetum glaucum* L.) as influenced by different weed management practices. *Andhra Pradesh J Agric Sci* 1:85–89

Mitra B, PM Bhattacharya, A Ghosh, K Patra, AK Chowdhury, MK Gathala (2018). Herbicide options for effective weed management in zero-till maize. *Ind J Weed Sci* 50:137–141

Mohammad YY, HA Bagudo, OD Uke (2021). Effects of weed control on growth and yield of pearl millet (*Pennisetum glaucum* L) in the Sudan Savanna, Sokoto State, Nigeria. *J Curr Opin Crop Sci* 2:155–164

Munde SD, VD Aghav, RD Pagar, JC Patel (2012). Effect of herbicides on weeds and yield of rainy season pearl millet. *Crop Res* 44:288–291

Nourou AIM, AK Saidou, W Arifa, AO Abdoulaye, JB Aune (2020). Intensification of pearl millet production in Niger through mechanized sowing and weeding, seed priming, seed treatment and microdosing. *Agronomy* 10:629

Pawar PP, SG Mehetre, SM Dhadge, NB Tarde (2021). Effect of pre and post emergence herbicides application on growth and yield of pearl millet (*Pennisetum glaucum* L). *Pharm Innov J* 10:780–782

Powles SB, Q Yu (2010). Evolution in action: Plants resistant to herbicides. *Annu Rev Plant Biol* 61:317–347

Ram B, GR Chaudhary, AS Jat, ML Jat (2005). Effect of integrated weed management and intercropping systems on growth and yield of pearl millet. *Ind J Agron* 50:210–213

Ram B, GR Chaudhary, AS Jat, ML Jat (2004). Nutrient depletion by weeds, weed control efficiency and productivity of pearl millet (*Pennisetum glaucum*) as influenced by intercropping systems and integrated weed management. *Ind J Agric Sci* 74:534–538

Rangani G, M Noguera, R Salas-Perez, L Benedetti, N Roma-Burgos (2021). Mechanism of resistance to s-metolachlor in *Palmer amaranth*. *Front Plant Sci* 12:652581

Rasool T, A Zohaib, Ehsanullah, R Ahmad, T Abbas, T Tabassum, MA Nadeem, Mahmood-ul-Hassan (2017). Forage yield and quality in pearl millet-sesbania intercropping system under various geometrical patterns. *Pak J Agric Res* 30:75–84

Satyavathi CT, S Ambawat, V Khandelwal, RK Srivastava (2021). Pearl millet: a climate-resilient nutricereal for mitigating hidden hunger and provide nutritional security. *Front Plant Sci* 12:659938

Singh H, ML Reager, S Kumar, B Kumar (2017). Influence of intercropping and weed control measures on yield component and nutrient content of pearl millet (*Pennisetum glaucum* L. Br. Emend Stuntz). *Intl J Curr Microbiol Appl Sci* 4:165–171

Singh U, SM Hiremath, SI Halikatti, GB Shashidhara, PL Patil (2011). Evaluation of herbicides for weed control in rainfed transplanted chilli (*Capsicum annuum* L.). *Karnat J Agric Sci* 24:125–128

Sousa BTD, ADES Pereira, LF Fraceto, HC Oliveira, G Dalazen (2022). Post-emergence herbicidal activity of nanoatrazine against *Alternanthera tenella* Colla plants compared to other weed species. *Heliyon* 8:e9902

Steel RGD, JH Torrie, DA Dickey (1997). *Principles and Procedures of Statistics*. McGraw Hill Cooperation Incorporation, New York

Vadez V, T Hash, FR Bidinger, J Kholova (2012). II 1.5 Phenotyping pearl millet for adaptation to drought. *Front Physiol* 3:386

Vighi M, M Matthies, KR Solomon (2017). Critical assessment of pendimethalin in terms of persistence, bioaccumulation, toxicity, and potential for long-range transport. *J Toxicol Environ Health B* 20:1–21

Wasnik VK, A Maity, D Vijay, SR Kantwa, CK Gupta, V Kumar (2017). Efficacy of different herbicides on weed flora of berseem (*Trifolium alexandrium* L.). *Range Manage Agrofor* 38:221–226

Yusuf MJ, IG Nab, A Basit, SK Husnain, LH Akhtar (2012). Development of high yielding millet variety “Sargodha Bajra-2011” released for general cultivation in Punjab Province of Pakistan. *Pak J Agric Sci* 49:275–282

Zemolin CR, LA Avila, GV Cassol, JH Massey, ER Camargo (2014). Environmental fate of s-metolachlor: A review. *Plant Danin* 32:655–664