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Full Length Article

Enhancing the Halosulfuron Efficacy by Alkyl Ether Sulfate Adjuvant for Control of *Parthenium hysterophorus* in Tomato

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Abstract

Combined application of foliar herbicides with adjuvants can provide a reliable parthenium weed management option for tomato growers. A two-year field study was conducted to evaluate the effects of alkyl ether sulfate (AES) adjuvant and *Achyranthes aspera* plant extract (AAE) on efficacy of herbicide against parthenium weed in tomato. The treatments were post-emergence foliar spray of halosulfuron at its full (49.4 g active ingredient ha^{-1}) and 25% reduced doses alone and in mixture with AES adjuvant and AAE. Results indicated that AES adjuvant performed better than AAE, as herbicidal treatments having AES adjuvant gave a more satisfactory weed control and higher tomato fruit yield than given by those having AAE. As compared to sole application of both the full and reduced herbicide doses, their tank-mixed applications along with AES caused significantly lower parthenium dry biomass (up to 27% and 28%) and nitrogen (up to 27% and 34%), phosphorus (up to 10% and 35%) and potash (up to 26% and 34%) uptakes resulting in significant increase in tomato plant height (up to 13% and 6%), leaves plant^{-1} (up to 9% and 11%), fruits plant^{-1} (up to 24% and 46%), single fruit weight (up to 9% and 6%), and fruit yield (up to 13% and 44%) during the years 2018 and 2019, respectively. Halosulfuron reduced dose in combination with AES adjuvant gave weed control efficacy (62% and 63%), herbicide efficacy index (1.97 and 2.19) and fruit yield (10.5 t ha^{-1} and 10.8 t ha^{-1}) during the years 2018 and 2019, respectively that were statistically similar to those observed with its full dose alone. It can be concluded that halosulfuron efficacy could be enhanced and its dose could be reduced up to 25% by its tank-mixed application with AES adjuvant without compromising tomato yield and quality.

Keywords: *Achyranthes aspera*; Alkyl ether sulfate; Flowering; Fruit quality; Herbicide efficacy

Introduction

Tomato (*Solanum lycopersicum* L.) is the third most widely grown vegetable in the world, after potato and sweet potato. A total of its 186.1 million metric tons of tomato are produced worldwide (FAOSTAT 2024). In Pakistan, tomato is the second most important vegetable grown on 68000 ha with a production of 762000 tons (GOP 2024). Parthenium weed (*Parthenium hysterophorus* L.) is a broadleaf weed of *Asteraceae* family that germinates in spring and matures in autumn (Adkins *et al.* 2018). It is a serious weed of tomato and caused considerable reduction in its fruit yield (Nishanthan *et al.* 2015). Halosulfuron gives good control of parthenium weed in tomato (Reddy *et al.* 2007). It belongs to the sulfonylurea herbicide family that inhibits acetolactate synthase (ALS) enzyme and can safely be used for post-emergence weed control in tomato (Buker *et al.* 2004). The safe interval between the application of this herbicide and tomato harvest is 2 weeks after transplanting to avoid any crop injury or detrimental effect on final yield (Buzanini and Boyd 2023). Sulfonylureas are highly phytotoxic and give effective weed control at much lower concentrations as these hydrolyze in acid medium 10-1000 times faster than other herbicides (Fenoll *et al.* 2012). As sustained control of parthenium weed requires consistent use of higher herbicide doses, intensive usage of persistent herbicides can cause environmental contamination, soil and water pollution, and health hazards (Moretti *et al.* 2002). This is especially true in case of vegetables as these are eaten in fresh form (Grewal *et al.* 2017). The maximal residue limit for halosulfuron in tomato is 50 parts per billion (ppb) (μg kg^{-1}) (IMRLD 2024). Therefore, herbicide doses need to be reduced in vegetables for controlling parthenium weed. One of the viable strategies could be the use of adjuvants (Idziak *et al.* 2023) or allelopathic plant extracts (Sarić-Krsmanović *et al.* 2020) as their tank-mixed application with reduced herbicide dose.

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Table 1: Soil analysis of the experimental site located at College of Agriculture, University of Sargodha, Sargodha, Pakistan

Soil characteristics	Unit	Year					
		2018			2019		
		0-15 cm	15-30 cm	Mean	0-15 cm	15-30 cm	Mean
pH	-	7.7	7.8	7.75	7.8	7.9	7.85
Electrical conductivity	dS m^{-1}	1.73	1.80	1.76	1.76	1.79	1.77
Organic matter	%	0.90	0.55	0.72	0.93	0.53	0.73
Total Nitrogen	%	0.043	0.039	0.041	0.045	0.040	0.042
Available P	ppm	8.4	4.1	6.25	8.5	4.2	6.35
Available K	ppm	162	148	155	165	155	166
Texture	-	Loam			Loam		

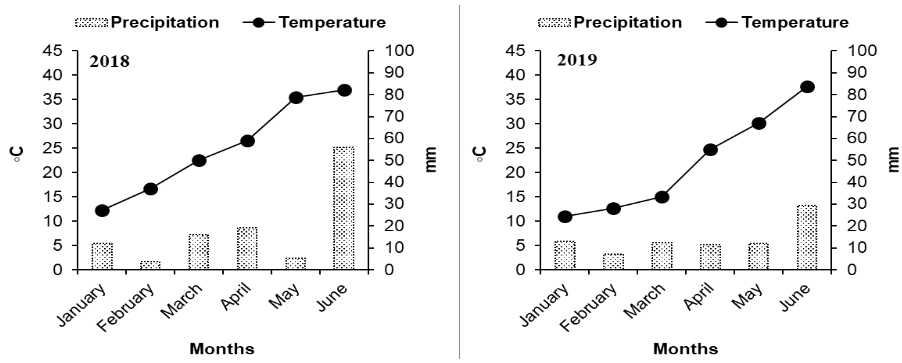

Fig. 1: Weather data of growing seasons during year 2018 and 2019

Alkyl ether sulfate is a potential adjuvant since it can reduce the amount of herbicide used without compromising its efficiency and increases crop yield (Tanveer *et al.* 2017). It is a polyethylene glycol mono-C12-14-alkyl ether sulfate sodium salt that acts as anionic surfactant. It has a C_{12}-C_{14} carbon chain attaching with it two moles of ethylene oxides. It increases the efficacy of herbicide by increasing its spreadability and penetration (Anderson 2021). Kammler *et al.* (2008) showed that several types of adjuvants enhanced the effectiveness of halosulfuron against hairy crabgrass (*Digitaria sanguinalis*) and smooth crabgrass (*D. ischaemum*) in pumpkin (*Cucurbita pepo* L.). *Achyranthes aspera* L. commonly called prickly-chaff flower has been proved to be highly allelopathic plant against parthenium weed (Safdar *et al.* 2016). Safdar *et al.* (2020) noted that for controlling parthenium weed in okra, halosulfuron dose could be reduced by its mixed application along with alkyl ether sulfate adjuvant. It was hypothesized that alkyl ether sulfate adjuvant and *A. aspera* plant extract could be used to minimize the dose of halosulfuron in tomato aimed at controlling parthenium weed. A field study was therefore planned to explore the potential of alkyl ether sulfate and *A. aspera* plant extract to enhance the efficacy of halosulfuron against parthenium weed in tomato crop.

Materials and Methods

Site description

Field experiments were performed at research area of College of Agriculture, University of Sargodha, Punjab, Pakistan during spring seasons of years 2018 and 2019. Before experiment, physico-chemical analysis of soil was worked-out (Table 1). Meteorological data were obtained from Agricultural Meteorology Cell (In-service Training Institute Sargodha, Pakistan) (Fig. 1).

Nursery sowing/transplanting and plant extract preparation

Nursery of tomato variety Rio Grande was sown on beds with seed rate of 2.5 g per m^2 during the month of December in each year. During frost period, nursery seedlings were kept covered with polythene sheet and were transplanted in field during the month of February (45 days after sowing). Transplanting was done manually on 60 cm apart ridges at 45 cm plant to plant spacing. Net plot size was 3.6 m × 1.8 m with planting density of 24 seedlings per plot. Total area of experimental field was 192 m^2. To get extract of *Achyranthes aspera*, an allelopathic plant, actively growing mature plants of *A. aspera* were collected, dried and whole plants (root, stem, leaves and inflorescence) were cut into small pieces. Those were kept soaked in distilled water at 1:20 w/v plant material: water ratio for a period of 24 h at room temperature (30°C ± 4) (Hussain and Gadoon 1981). Its aqueous extract was then obtained by filtering through ASTM 40 mesh sieve and then through Sartorious Minisart syringe filters of 0.45 μm pore size.

Experimental treatments

The treatments in both years' experiments included post-emergence application of halosulfuron-methyl (Orchus Gold 80 WDG) at its full dose [49.4 g active ingredient (a.i.) ha^{-1}], 25% reduced dose alone, full dose + alkyl ether sulfate (AES) as adjuvant, 25% reduced dose + AES adjuvant, full dose + *A. aspera* extract (AAE), 25% reduced dose + AAE, 25% reduced dose + AES + AAE. Each treatment was replicated thrice, and randomized complete block design was used. Seeds of parthenium weed having 90% germination at 200 seeds per m^2 were uniformly broadcasted throughout the field just before crop transplanting. Just after parthenium weed emergence, herbicide was sprayed in each plot in accordance with the treatment plan using a hand-operated knapsack spray (FST, model 20DE). Before applying herbicides, the spray volume was calibrated to determine the precise amount of water (300 L ha^{-1}) required. All other weeds except parthenium were uprooted manually. All other crop management practices were uniformly carried out during whole growing season. Nitrogen at 145 kg ha^{-1}, phosphorus at 58 kg ha^{-1}, and potassium at 80 kg ha^{-1} were applied in the form of urea, diammonium phosphate and sulphate of potash at the time of planting.

Observations and data recording

Parthenium growth parameters: All parthenium plants from an area of 1 m^2 of each plot were harvested and after an initial shade drying, subjected to oven-drying at 70°C for 48 h. Parthenium dry biomass (g m^{-2}) was measured by electronic balance. For estimating the parthenium nitrogen (N), phosphorus (P) and potash (K) uptakes (kg ha^{-1}), 1 g of powdered sample from oven-dried parthenium plants of each treatment was mixed with 10 mL H_2SO_4 in a conical flask and left overnight. Afterward, 5 mL of H_2O_2 were added and flasks were placed on the hot plate and heated slowly until the mixture became colorless transparent. Then each digested sample was diluted to 50 mL by using distilled water and stored into clean plastic bottle. For N determination, 10 mL of diluted sample was drawn for distillation of NH_3 in the presence of 40% NaOH by using a micro-Kjeldhal's apparatus. N was gathered in the form of NH_3 in a receiver of micro-Kjeldhal's apparatus, having 4% solution of boric acid, beside indicators (methyl red and bromocresol green) and titration was carried out alongside 0.1 *N* H_2SO_4. P was determined by using spectrophotometer (Beckman) and flame photometer (Jenway 8505) was used for the determination of K. Parthenium dry biomass was multiplied with N, P and K contents to get parthenium N, P and K uptakes, respectively.

Weed control efficacy (WCE) was assessed by the formula of Main *et al.* (2007) as:

$$WCE = \frac{W2 - W1}{W1} \times 100 \quad (1)$$

Where, W1 = Weed Dry biomass in check plots and W2 = Weed Dry biomass in treated plots.

Herbicide efficacy index (HEI) was calculated for each treatment with the help of formula given by Das (2013) as follow:

$$HEI = \frac{Yt - Yc}{Yc} \times 100 \,/\, \frac{DMt}{DMc} \times 100 \quad (2)$$

Where, Yc and Yt were yields of check and treated plots, and DMc and DMt were weed dry matters in check and treated plots, respectively.

Tomato growth, yield and fruit quality parameters: Tomato plant height at maturity was measured from the ground level to the plant apex with a meter rod from ten randomly chosen plants per plot. The average plant height was then calculated. Days taken to 50% flowering and maturity were determined by assuming that 50% of pre-tagged plants from each experimental plot produced flowers after being transplanted into the field. Days to maturity were noted when maximum number of fruits on plants attained maximum size in each experimental plot.

To take leaves per plant of tomato, leaves from 10 randomly selected plants at maturity from each plot were counted manually and then their means were taken. Fruits' number per plant was calculated by taking sum of fruits counted from all the 3 harvests from every plot. Weight of single fruit was calculated by dividing the fruit weight per plant to fruits per plant. Harvesting of tomato fruits were done through intervals of five days since the initiation of fruiting (120 days after transplanting). Total fruit yield of all pickings was recorded from every experimental plot and then converted into t ha^{-1}.

To determine the crude fiber contents of a defatted sample, Shahnawaz *et al.* (2009) method was used. In accordance with it, 200 mL of 1.25% H_2SO_4 were added to 2 g of fruit sample that was free of fat and moisture. The remaining material was treated with 1.25% NaOH after washing and filtering using Whatman paper No. 4. After being treated with 1% HNO_3, it was filtered and given two hot water washings. The ash content of the residue was measured after it was burned. Weight loss resulted in the weight of crude fiber. Total soluble solids were assessed by following the standard AOAC (1995) method.

Statistical analysis

With the aid of Statistix 8.1 software, the obtained data was subjected to Fisher's analysis of variance (ANOVA) approach (Steel *et al.* 1997), and Tukey's honestly significant difference (HSD) test was used as means' separation test at the 5% probability level. The single degree of freedom (df) contrast approach was used to organize the planned eloquent contrast comparisons (Little and Hills 1978).

Results

Parthenium growth

Across both the years, when compared to untreated control, all herbicide treatments significantly reduced dry biomass of parthenium weed (Table 2). As compared to their sole applications, both the full and reduced doses of halosulfuron

Table 2: Comparative effect of different herbicide treatments on parthenium growth and nutrients' uptake in tomato

Treatments	Weed dry biomass (g m^{-2})		Nitrogen uptake (kg ha^{-1})	
	2018	2019	2018	2019
Control (no herbicide)	178.0 a	166.1 a	50.4 a	48.6 a
Halosulfuron (post-emergence) full dose	71.2 d	65.1 cd	25.4 c	24.9 c
Halosulfuron 25% reduced dose alone	95.3 b	76.0 b	30.9 b	32.2 b
Halosulfuron full dose + AES	55.1 f	47.1 e	20.1 f	18.1 e
Halosulfuron 25% reduced dose + AES	68.3 de	60.7 cd	22.6 de	21.4 d
Halosulfuron full dose + AAE	64.4 e	57.2 d	21.3 ef	19.7 de
Halosulfuron 25% reduced dose + AAE	81.3 c	67.3 c	25.1 c	25.8 c
Halosulfuron 25% reduced dose + AES + AAE	72.6 d	60.0 cd	23.0 d	20.2 d
HSD	5.35	8.13	1.35	1.96
		Contrast		
Control *vs.* All	178.0 *vs.* 72.6**	166.1 *vs.* 62.0**	50.4 *vs.* 24.1**	48.7 *vs.* 23.2**
AES *vs.* AAE	67.1 *vs.* 72.6*	54.5 *vs.* 62.3*	21.4 *vs.* 23.3*	19.8 *vs.* 22.8**
Treatments	Phosphorus uptake (kg ha^{-1})		Potassium uptake (kg ha^{-1})	
	2018	2019	2018	2019
Control (no herbicide)	7.84 a	7.26 a	44.9 a	42.2 a
Halosulfuron (post-emergence) full dose	3.37 d	3.18 d	23.1 c	22.4 c
Halosulfuron 25% reduced dose alone	4.53 b	4.61 b	28.4 b	29.2 b
Halosulfuron full dose + AES	3.12 e	2.85 e	18.4 f	16.5 f
Halosulfuron 25% reduced dose + AES	3.24 de	2.99 de	20.7 de	19.5 d
Halosulfuron full dose + AAE	3.22 de	2.88 de	19.6 ef	17.6 ef
Halosulfuron 25% reduced dose + AAE	3.70 c	3.72 c	23.0 c	23.4 c
Halosulfuron 25% reduced dose + AES +AAE	3.32 de	2.89 de	21.0 d	18.3 e
HSD	0.254	0.311	1.23	1.09
		Contrast		
Control *vs.* All	7.84 *vs.* 3.50**	7.26 *vs.* 3.30**	44.9 *vs.* 22.1**	42.2 *vs.* 21.0**
AES *vs.* AAE	3.18 *vs.* 3.47^{NS}	2.92 *vs.* 3.30^{NS}	19.6 *vs.* 21.4*	218 *vs.* 20.6**

Figures in a column with dis-similar lettering significantly vary from one another at 5% probability level according to Tukey's honestly significant difference (HSD) test, AES = alkyl ether sulfate, AAE = *Achyranthes aspera* extract, * = Significant at 5% probability, ** = Significant at 1% probability, NS = Non-significant

in combination with alkyl ether sulfate (AES) caused significant reductions (up to 27% and 28%) in weed dry biomass, respectively. During both years, in comparison to its full dose, halosulfuron 25% reduced dose showed up to 33% lower efficacy as evident by the significant increase in dry biomass of parthenium. However, halosulfuron reduced dose tank-mixed with AES attained parthenium weed control efficacy (WCE) statistically similar to that of halosulfuron full dose alone in both the years (Fig. 2a). The contrast analysis indicated that although both the AES and *Achyranthes aspera* extract (AAE) enhanced the efficacy of halosulfuron during both years, yet AES was proved to be superior than AAE in this regard (Table 2). The comparison of herbicide efficacy indices (HEIs) (Fig. 2b) also showed statistically higher HEI of 25% reduced dose of halosulfuron + AES than that of 25% reduced dose of halosulfuron + AAE during both the years of study.

All herbicide treatments significantly reduced the parthenium uptakes of nitrogen (N), phosphorus (P) and potash (K) (Table 2). Among all herbicide treatments, the lowest N uptake (20.1 and 18.1 kg ha^{-1}), P uptake (3.12 and 2.85 kg ha^{-1}) and K uptake (18.4 and 16.5 kg ha^{-1}) by parthenium weed occurred with halosulfuron full dose in combination with AES during first and second years, respectively. During both years, in comparison to full halosulfuron dose, significant increase in parthenium NPK uptakes occurred with reduced dose of halosulfuron alone but not with either the AES or AAE. Even, reduced halosulfuron dose in mixture with AES caused further decrease in parthenium NPK uptakes as compared to its sole application. Contrast analysis also highlighted that AES caused greater enhancement in halosulfuron efficacy than given by AAE.

Tomato growth, yield and fruit quality

Data indicated that all herbicide treatments significantly improved the plant height and leaves plant^{-1} of tomato and hastened its flowering and maturity (Table 3). Among all herbicide treatments, significantly the highest plant height (61.1-63.8 cm and 59.0-64.0 cm) and leaves plant^{-1} (70.6-73.3 and 72.8-75.3) of tomato were recorded with halosulfuron full dose alone as well as in combination with AES and AEE during first and second years, respectively. However, by reducing halosulfuron dose, plant height and leaves plant^{-1}of tomato also decreased. But application of reduced halosulfuron dose in mixture with both the AES and AAE did not caused significant decrease in plant height and leaves plant^{-1}of tomato. Data showed that in comparison to untreated weedy check, herbicide application hastened the flowering and maturity of tomato during both the years of study (Table 3). Among all herbicide treatments, full dose of halosulfuron in combination with AES was proved to be the best as it resulted in 13 days earlier flowering and 14 days earlier maturity of tomato.

It is obvious from data that compared to untreated weedy check, all herbicide treatments caused significant increase in fruit yield and its associative traits *i.e.*, number

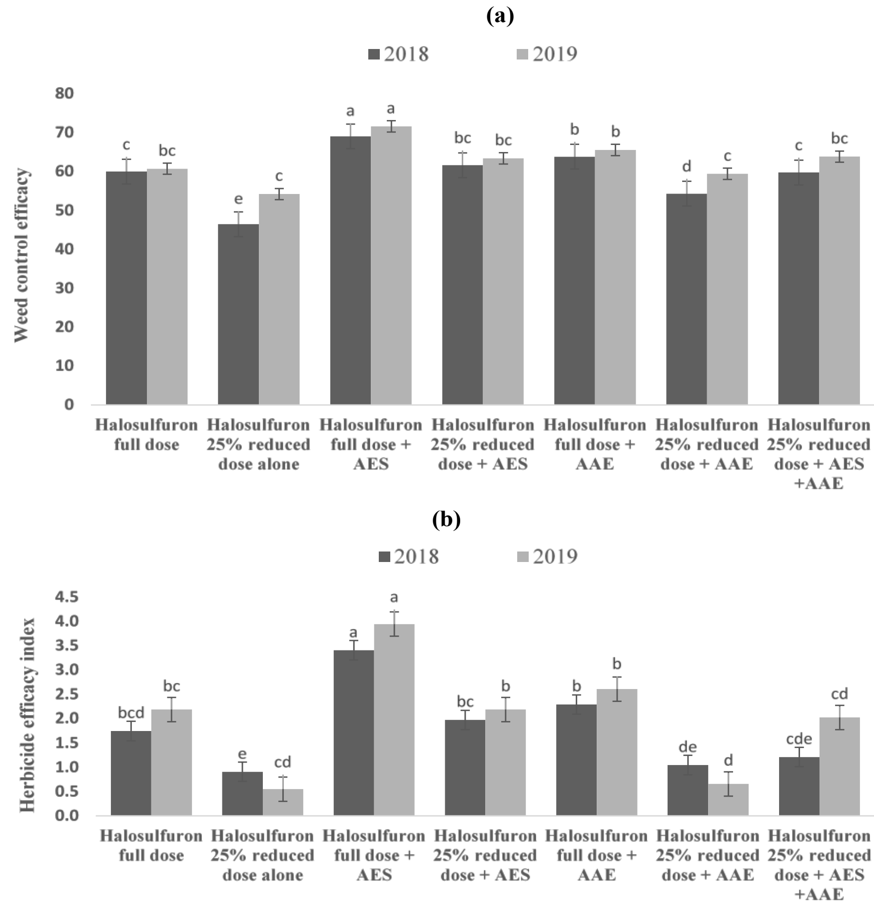

Fig. 2: Comparison of (**a**) weed control efficacies (%) and (**b**) herbicide efficacy indices of different herbicide treatments

of fruits per plant and single fruit weight (Table 4). The full dose of halosulfuron in combination with AES resulted in the highest number of fruits (25 and 24 plant^{-1}) and single fruit weight (91.3 and 92.6 g) during first and second year, respectively. This treatment remained statistically at par with halosulfuron full dose + AAE regarding fruits per plant and single fruit weight during both the years. However, reduced halosulfuron dose resulted in significant decline in these parameters but a mixture of reduced halosulfuron dose with AES and AES +AAE attained statistically similar values of fruits per plant and single fruit weight to those recorded with its full dose. It means that AES enhanced the efficacy of halosulfuron to such an extent that its lower dose along with AES gave similar performance as shown by its full dose. The contrast analysis also proved AES to be better than AAE (Table 4).

It is obvious from the data that in comparison to untreated control, all herbicide treatments resulted in significant increase in fruit yield of tomato (Table 4). However, significantly the highest fruit yield (12.2 and 12.7 t ha^{-1}) of tomato, during first and second year, respectively was recorded with full dose of halosulfuron + AES. This treatment was followed by full dose of halosulfuron + AAE. It is noticed that in comparison to full and reduced halosulfuron doses alone, their mixed applications along with AES adjuvant resulted in significant increases in tomato fruit yield during both years. The comparison of herbicides' efficacy indices (Fig. 2b) indicated significant enhancements in efficacies of full as well as reduced halosulfuron doses by the addition of AES adjuvants in terms of percent crop yield increases per unit weed dry biomass decreases. The contrast analysis indicated that among both additives, AES was proved superior to AAE during both the years (Table 4).

The results revealed that application of herbicide for the control of parthenium significantly increased the TSS (Total Soluble Solids) but not significantly influenced the fiber content of tomato fruit (Table 5). The highest TSS (6.36-6.37% and 6.31-6.33%) in the first and second years respectively was detected with the treatments that received halosulfuron full dose with AES or AAE. It is obvious from the data that TSS of tomato fruit was significantly declined in response to reduced halosulfuron dose when compared to that recorded with its full dose during both years. But no significant decrease in this parameter was recorded when the reduced dose was mixed with AES. The contrast analysis indicated that both the AES and AAE showed equal performance in both the years of study.

Table 3: Comparative effect of herbicide treatments on tomato growth

Treatments	Plant height (cm)		Number of leaves plant^{-1}	
	2018	2019	2018	2019
Control (no herbicide)	43.7 e	44.0 e	59.6 e	56.4 e
Halosulfuron (post-emergence) full dose	54.3 c	56.4 c	67.0 bc	67.9 bc
Halosulfuron 25% reduced dose alone	49.2 d	50.8 d	63.5 d	61.4 d
Halosulfuron full dose + AES	63.8 a	64.0 a	73.3 a	75.3 a
Halosulfuron 25% reduced dose + AES	52.7 c	52.6 c	65.7 c	68.4 b
Halosulfuron full dose + AAE	62.1 a	60.6 ab	70.6 ab	72.8 a
Halosulfuron 25% reduced dose + AAE	59.6 b	59.0 ab	67.5 bc	65.8 bc
Halosulfuron 25% reduced dose + AES + AAE	61.6 a	59.9 ab	64.4 cd	64.7 c
HSD	2.26	6.05	3.64	3.23
	Contrast			
Control *vs.* All	43.7 *vs.* 57.4**	44.0 *vs.* 57.9**	59.67 *vs.* 67.45**	56.47 *vs.* 68.09**
AES *vs.* AAE	57.8 *vs.* 58.2^{NS}	58.3 *vs.* 60.3^{NS}	69.52 *vs.* 69.07*	71.88 *vs.* 69.35*
Treatments	Days to 50% flowering		Days to maturity	
	2018	2019	2018	2019
Control (no herbicide)	56.7 a	56.3a	105.2 a	103.3 a
Halosulfuron (post-emergence) full dose	47.4 de	47.0 de	97.0 bc	94.6 bc
Halosulfuron 25% reduced dose alone	53.1 b	52.6 b	100.2 ab	98.3 ab
Halosulfuron full dose + AES	43.4 f	43.0 f	90.9 c	89.0 c
Halosulfuron 25% reduced dose + AES	50.1 cd	49.6 cd	98.2 abc	96.3 abc
Halosulfuron full dose + AAE	45.4 ef	45.0 ef	96.6 bc	95.0 bc
Halosulfuron 25% reduced dose + AAE	52.7 bc	52.3 bc	99.6 ab	97.6 ab
Halosulfuron 25% reduced dose + AES +AAE	48.4 d	48.0 d	97.9 abc	96.3 abc
HSD	2.94	2.94	7.79	8.06
	Contrast			
Control *vs.* All	56.8 *vs.* 48.7**	56.3 *vs.* 48.2**	105.3 *vs.* 97.3*	103.3 *vs.* 95.5*
AES *vs.* AAE	46.8 *vs.* 49.1^{NS}	46.3 *vs.* 48.7^{NS}	94.6 *vs.* 98.1^{NS}	92.7 *vs.* 96.8^{NS}

Figures in a column with dis-similar lettering significantly vary from one another at 5% probability level according to Tukey's honestly significant difference (HSD) test, AES = alkyl ether sulfate, AAE = *Achyranthes aspera* extract, * = Significant at 5% probability, ** = Significant at 1% probability, NS = Non-significant

Table 4: Comparative effect of herbicide treatments on fruit yield and related traits of tomato

Treatments	Number of fruits plant^{-1}		Single fruit weight (g)		Fruit yield (t ha^{-1})	
	2018	2019	2018	2019	2018	2019
Control (no herbicide)	10.3 f	9.6 e	71.7 e	74.8 f	6.0 e	6.3 d
Halosulfuron (post-emergence) full dose	21.3 bc	19.3 bc	83.7 bc	88.0 bc	10.8 b	11.2 b
Halosulfuron 25% reduced dose alone	15.3 e	16.6 d	78.2 d	81.4 e	8.8 d	7.5 c
Halosulfuron full dose + AES	25.0 a	24.0 a	91.3 a	92.6 a	12.2 a	12.7 a
Halosulfuron 25% reduced dose + AES	22.0 bc	20.6 b	81.7 bcd	86.8 bcd	10.5 b	10.8 b
Halosulfuron full dose + AAE	22.3 ab	22.0 ab	87.7 a	89.0 ab	10.8 b	11.4 b
Halosulfuron 25% reduced dose + AAE	18.3 d	17.0 d	78.9 d	83.1 de	8.8 cd	7.8 c
Halosulfuron 25% reduced dose + AES +AAE	19.3 cd	19.0 bcd	80.9 bcd	84.1 cde	8.8 bc	10.4 b
HSD	2.80	2.55	4.05	4.26	1.22	1.08
	Contrast					
Control *vs.* All	10.3 *vs.* 20.5**	9.7 *vs.* 9.6**	71.7 *vs.* 83.0**	74.8 *vs.* 86.4**	6.0 *vs.* 10.0**	6.7 *vs.* 10.3**
AES *vs.* AAE	23.5 *vs.* 21.8**	22.3 *vs.* 19.5**	87.5 *vs.* 82.3**	89.7 *vs.* 86.0*	11.6 *vs.* 9.7*	11.8 *vs.* 9.6**

Figures in a column with dis-similar lettering significantly vary from one another at 5% probability level according to Tukey's honestly significant difference (HSD) test, AES = alkyl ether sulfate, AAE = *Achyranthes aspera* extract, * = Significant at 5% probability, ** = Significant at 1% probability, NS = Non-significant

Discussion

Tomatoes are highly susceptible to competition from weeds, especially in the initial phases following transplanting that has detrimental effects on tomato development, growth, and flowering that significantly reduce yield (Hussain *et al*. 2016; Mennan *et al*. 2020). Due to stunted growth of tomato and availability of wider plant spacing in its fields, this crop has been badly suffered from parthenium weed infestation in Pakistan and many other countries (Khan *et al*. 2014; Muhammad *et al*. 2015; Yaacoby *et al*. 2023). Post-emergence herbicides offer quick and sustained control of parthenium weed but their doses should be minimized to a level leaving no herbicidal residues on vegetables. This is because, human health may be affected by the utilization of vegetables contaminated with herbicide residues. Adjuvants (Idziak *et al.* 2023) and allelopathic plant extracts (Sarić-Krsmanović *et al.* 2020) have ability to enhance the efficacy of a post-emergence herbicide when applied in combination with it. Thus, herbicide dose could be reduced by adjuvant or allelopathic plant extract.

The present studies revealed that efficacies of full and reduced halosulfuron doses were enhanced up to 27% and 28%, respectively as shown by the respective parthenium biomass decreases from those observed with their sole applications. Halosulfuron reduced dose in combination with alkyl ether sulfate (AES) adjuvant gave similar parthenium dry biomass and weed control efficacy (percent dry weight

Table 5: Comparative effect of herbicide treatments on fruit quality of tomato

Treatments	TSS (%)		Fiber content (%)	
	2018	2019	2018	2019
Control (no herbicide)	5.20 e	5.16 e	0.40	0.41
Halosulfuron (post-emergence) full dose	6.17 b	6.13 b	0.59	0.57
Halosulfuron 25% reduced dose alone	5.97 c	5.93 c	0.49	0.55
Halosulfuron full dose + AES	6.37 a	6.33 a	0.60	0.63
Halosulfuron 25% reduced dose + AES	6.07 bc	6.03 bc	0.57	0.57
Halosulfuron full dose + AAE	6.36 a	6.31 a	0.58	0.58
Halosulfuron 25% reduced dose + AAE	5.77 d	5.73 d	0.56	0.48
Halosulfuron 25% reduced dose + AES +AAE	6.07 bc	6.03 bc	0.52	0.49
HSD	0.1324	0.1324	NS	NS
		Contrast		
Control *vs.* All	5.20 *vs.* 6.11**	5.16 *vs.* 6.08**	-	-
AES *vs.* AAE	6.17 *vs.* 6.07^{NS}	6.33 *vs.* 5.83^{NS}	-	-

Figures in a column with dis-similar lettering significantly vary from one another at 5% probability level according to Tukey's honestly significant difference (HSD) test, AES = alkyl ether sulfate, AAE = *Achyranthes aspera* extract, TSS = Total Soluble Solids, * = Significant at 5% probability, ** = Significant at 1% probability, NS = Non-significant

reduction over untreated weedy check) as those observed with its full dose alone. The enhancement in efficacy of halosulfuron against parthenium weed by its mixed application along with AES seems to be due to its role as surfactant that improved the spreadability of herbicide over the plant foliage and its penetration into the plant through leaf cuticle (Anderson 2021). While, to some extent, *Achyranthes aspera* plant extract (AAE) also augmented halosulfuron efficacy probably due to its higher phenolics' composition like chromatotropic acid (63.8 mg L^{-1}), gallic acid (16.9 mg L^{-1}), caffeic acid (7.4 mg L^{-1}), 4-hydroxy-3-methoxy benzoic acid (24.8 mg L^{-1}), m-coumaric acid (3.1 mg L^{-1}) and syringic acid (9.2 mg L^{-1}) (Safdar *et al.* 2016). The present findings are comparable to those of Safdar *et al.* (2020) who showed that AES enhanced the efficacy of halosulfuron against parthenium in terms of decreasing its density and dry weight in okra. Safdar *et al.* (2021) suggested that mixing AES with 80% reduced lactofen dose gave same control of clustered-flower snoutbean [*Rhynchosia capitata* (Roth.) DC] as given by its full dose. In comparison to halosulfuron full dose alone, its 25% reduced dose along with AES caused a further more reduction in N, P and K uptakes per unit area by parthenium weed certainly due to its reduced biomass per unit. Similar outcomes were reported by Asif *et al.* (2019) who demonstrated that 25% reduced dose of dicamba along with 2% ammonium sulfate solution as adjuvant resulted in statistically similar uptake of N, P and K by parthenium weed as given by its full dose alone.

The results showed that in comparison to reduced halosulfuron dose alone, its tank-mixed application along with either the AES or AAE resulted in improvement in growth of tomato in terms of plant height, number of leaves and earlier flowering and maturity that was comparable to that observed with its full dose alone. Even, somewhat enhancement in tomato plant height was observed with halosulfuron reduced dose in combination with both the AES and AAE. It indicates that both of these additives showed synergistic action in enhancing the efficacy of halosulfuron on parthenium weed. In addition, it could be perceived that by reducing halosulfuron dose, its phytotoxicity against tomato crop was also reduced. Thus, increased efficacy on parthenium weed and reduced phytotoxic action against tomato crop leads to improvement in vegetative growth of tomato. Therefore, in comparison to halosulfuron alone, its tank-mixed application along with both additives caused boost-up in growth, thus hastened flowering and maturity of tomato. This was the result of reduced parthenium infestation that alleviated inter-specific competition and enhanced nutrient uptake by the tomato thus its better growth and development. The delayed maturity of tomato in case of higher parthenium infestation might be the result of deposition of parthenium pollen on floral parts of tomato that inhibited its pollination and pollen tube germination (Kanchan and Jayachandra 1980). The results of the current study were supported by Safdar *et al.* (2021) who demonstrated that AES improved herbicide effectiveness. Asif *et al.* (2019) showed that in comparison to post-emergence application of full dose of dicamba alone, tank-mixed application of its 75% dose along with 2% ammonium sulfate as adjuvant resulted in higher stem height, stem diameter, leaves per plant, and yield of forage sorghum. According to Safdar *et al.* (2020), application of AES and AAE in combination with halosulfuron caused enhancement in efficacy of halosulfuron thus reducing parthenium dry weight, and increased plant height and leaves' count per plant of okra. According to present investigation, both the full and reduced herbicide doses along with AES adjuvant caused significantly the higher fruits plant^{-1} (up to 24% and 46%), single fruit weight (up to 9% and 6%), and fruit yield (up to 13% and 44%), respectively as compared to their applications without adjuvant. This argued that both of these additives enhanced the efficiency of this herbicide against parthenium. The reduced parthenium infestation and weed competition stress at later growth stages of tomato resulted in better flowering, greater fruit set (number) and its size. The parthenium weed may reduce number of fruits by interfering pollination and fertilization of crop through deposition of its pollen grains on floral parts of host crop (Kanchan and Jayachandra 1980). The enhanced fruit yield of tomato by herbicide application seems to be result of enhancement in fruits per plant and weight per fruit. Safdar *et al.* (2020) also showed a boost-up in pod yield, pod number per plant and pod length of okra due to better control of parthenium weed as a result of post-emergence halosulfuron application along with alkyl ether sulfate adjuvant.

The results of present studies indicated improvement in quality of tomato fruit in terms of higher TSS due to tank-mixed application of halosulfuron with alkyl ether sulfate as compared to that recorded with its sole application. It was attributed to better growing conditions with least parthenium infestation. According to Mohamed and Abdalla (2023), the TSS contents of tomato fruit were improved by herbicidal weed control. Kumar *et al.* (2013) found that integrated weed management using herbicide with one hand weeding gave the highest TSS contents in tomato fruit.

Conclusion

The herbicide halosulfuron gave effective control of parthenium by reducing its density, dry weight and NPK uptake thus improving the growth, yield and quality of tomato. However, its efficacy can be enhanced further by its application along with alkyl ether sulfate adjuvant. Moreover, dosage of this herbicide can be reduced up to 25% by its mixed application with alkyl ether sulfate to obtain the same efficiency as with its full dose without compromising tomato yield along with better fruit quality.

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Author Contributions

MES planned the experiments; MKA executed the study and collected experimental data; AA and MA statistically analyzed the data and interpreted the results; MAN made the write up and illustrations.

Conflict 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.

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