crops

Article

Herbicide Program to Control *Parthenium hysterophorus* in Grain Sorghum in an Arid Environment

Ali Ahsan Bajwa [1,2,*], Ahmad Nawaz [3,4], Muhammad Farooq [5], Bhagirath Singh Chauhan [2,6] and Steve Adkins [2]

[1] Department of Animal, Plant and Soil Sciences, AgriBio, La Trobe University, Melbourne, VIC 3086, Australia
[2] School of Agriculture and Food Sustainability, The University of Queensland, Gatton, QLD 4343, Australia; b.chauhan@uq.edu.au (B.S.C.); s.adkins@uq.edu.au (S.A.)
[3] Center for Agriculture and Biosciences International (CABI), Central and West Asia, Satellite Town, Rawalpindi 46300, Punjab, Pakistan; ahmadnawaz2006@gmail.com
[4] College of Agriculture, Bahauddin Zakariya University, Layyah 31200, Punjab, Pakistan
[5] Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Al-Khoud 123, Oman; farooqcp@squ.edu.om
[6] The Centre for Crop Science, Queensland Alliance for Agriculture and Food Innovation (QAAFI), The University of Queensland, Gatton, QLD 4343, Australia
* Correspondence: a.bajwa@latrobe.edu.au; Tel.: +61-431-194-862

Abstract: Parthenium weed (*Parthenium hysterophorus* L.) is an emerging production constraint in many summer crops including sorghum (*Sorghum bicolor* L. Moench), but limited control options are available. In this field study, the efficacy of sole and sequential applications of a pre-emergence (pendimethalin) and a post-emergence (bromoxynil) herbicide was evaluated for parthenium weed control in grain sorghum over two years. Pendimethalin or bromoxynil alone could only provide 54% and 63% control, whereas their sequential application provided 86% control of parthenium weed over the weedy treatment. The sorghum plants in pendimethalin followed by bromoxynil treatment had the highest leaf fresh weight per plant, plant dry biomass, plant height, and the number of heads among the herbicide treatments. Sorghum fresh forage yield, dry fodder yield, 1000-grain weight, and grain yield were highest in the weed-free treatment followed by the pendimethalin followed by (fb) bromoxynil treatment. Overall, the herbicide treatment performance was in an order of pendimethalin fb bromoxynil > bromoxynil > pendimethalin for weed control and sorghum yield improvement. These results suggest that pendimethalin followed by bromoxynil may provide acceptable control (>85%) of parthenium weed and may improve sorghum grain yield (up to 23%).

Keywords: weed control; *Sorghum bicolor*; parthenium weed; herbicides; grain yield

check for updates

Citation: Bajwa, A.A.; Nawaz, A.; Farooq, M.; Chauhan, B.S.; Adkins, S. Herbicide Program to Control *Parthenium hysterophorus* in Grain Sorghum in an Arid Environment. *Crops* **2023**, *3*, 292–301. https://doi.org/10.3390/crops3040026

Academic Editor: Kenneth J. Moore

Received: 18 September 2023
Revised: 13 October 2023
Accepted: 2 November 2023
Published: 16 November 2023

1. Introduction

Sorghum (*Sorghum bicolor* L. Moench) holds significant importance as a cereal and a forage crop in various regions globally, including Pakistan. In Pakistan, its cultivation spans over 0.34 million hectares [1]. The crop is primarily cultivated in semi-arid and arid parts of the country, particularly on marginal lands due to its resilience in low nutrient and harsh climatic conditions [2,3]. However, grain sorghum faces challenges from substantial weed growth, often exacerbated by limited financial resources preventing manual or mechanical weed removal by most farmers. Broadleaf weeds are a significant issue for sorghum cultivation due to the limited availability of selective herbicide options in this crop. Additionally, the proliferation of new weed species further exacerbates the situation, given the absence of tested herbicide options for their control.

Parthenium weed (*Parthenium hysterophorus* L.) is one such emerging weed species within Pakistan's crop production systems, as is the case in several other South Asian nations [4]. This invasive annual weed, belonging to the Asteraceae family, has spread to approximately 50 countries [5]. Initially regarded as an environmental weed with adverse effects on native biodiversity, human and animal health, and pasture productivity [5], it has recently emerged as a significant threat to crop production in tropical and sub-tropical regions [4,6]. In eastern Ethiopia, Parthenium weed was identified as the second most prevalent weed across 240 arable crop fields [7]. Similarly, it has been noted as a growing problematic weed species in sorghum cultivation in Pakistan [8].

Parthenium weed possesses distinctive biological and invasive characteristics that enable its establishment in various landscapes, allowing it to compete vigorously with other plant species [4,9,10]. Its robust growth patterns, efficient reproductive biology, rapid resource acquisition, ability to tolerate abiotic stress, allelopathic capacity, and phenotypic plasticity are among the pivotal traits contributing to its invasiveness and competitiveness [4,10–14]. Notably, parthenium weed infestations have been linked to significant yield losses in major field crops such as sorghum, maize (*Zea mays* L.), and rice (*Oryza sativa* L.) [15–18]. A recent study by Bajwa et al. [19] reported a grain yield reduction of up to 81% in sorghum due to competition from parthenium weed in Pakistan. Similarly, Tamado et al. [15] documented grain yield losses of up to 97% in sorghum due to severe parthenium weed infestations in arid conditions of Ethiopia. Therefore, effective management of parthenium weed is crucial to mitigate its adverse impacts on crop growth and yields. Although biological control of this species has shown relative success in non-cropped areas, it is unsuitable for managing this weed within crop production systems [20,21]. Consequently, chemical control remains a primary option to combat parthenium weed.

Several selective and non-selective herbicides have been employed in non-cropped areas, yielding varying degrees of success in parthenium weed control [22–24]. Yet only a limited number of studies have assessed herbicide options for this weed species within crop production systems [25–29]. In maize, the sole and combined applications of atrazine, bromoxynil, and S-metolachlor have been proven effective in controlling parthenium weed [27]. Tadesse et al. [26] demonstrated that a pre-emergence application of atrazine integrated with wheat straw mulch effectively controlled parthenium weed in grain sorghum in Ethiopia. However, the use of 2,4-D yielded inconsistent control of parthenium weed in grain sorghum in the same region [25]. Concerns about atrazine application causing injury to sorghum crops have been noted. Conversely, a pre-emergence application of pendimethalin effectively controlled weeds in sorghum, and the crop showed tolerance to herbicide doses up to 3 kg a.i. ha^{-1} in Nigeria [30]. In India, Tadesse [31] reported that a pre-emergence application of pendimethalin at a rate of 1 kg a.i. ha^{-1} provided effective control of parthenium weed in sorghum intercropped with cowpea [*Vigna unguiculata* (L.) Walp.]. In Mexico, post-emergence application of bromoxynil at different rates (480, 360, or 240 g a.i. ha^{-1}) achieved excellent control of major broadleaf weeds, including parthenium weed, in a grain sorghum crop [32]. Studies from the United States of America (USA) indicated that post-emergence application of pyrasulfotole plus bromoxynil effectively controlled various broadleaf weeds in grain sorghum with minimal crop injury that did not affect the final grain yield [33,34]. However, no study has evaluated the sequential application of pre- and post-emergence herbicides to control parthenium weed in grain sorghum, which could be more effective due to the complementary effects of the herbicides.

This field study was conducted to assess the potential of pendimethalin (pre-emergence), bromoxynil (post-emergence), and their sequential application to control parthenium weed in grain sorghum under arid conditions in Pakistan. The outcomes of this study aim to provide viable chemical control options for parthenium weed in grain sorghum cultivated in arid conditions.

2. Materials and Methods

2.1. Field Experiment Site

A field study was conducted at the Research Farm of Bahauddin Zakariya University, situated in Layyah, Pakistan (coordinates: 30.96° N, 70.93° E, and altitude: 143 m). The study was executed in 2016 and replicated in 2017 at the same location. The region experiences a desert climate, characterized by an average annual rainfall below 200 mm. During the crop growing season from July to October, the total rainfall was recorded as 207 mm in 2016 and 103 mm in 2017 (source: Adaptive Research Farm, Karor, Layyah). Throughout both years, the average maximum and minimum temperatures during the growing season were 33 °C and 20 °C, respectively. The soil at the site was classified as sandy loam (parent material rolling sand plains and fresh alluvium; dominant soil series Bhakkar, Banda, Bhutesar, Fazilpur and Shahdara). The soil featured a 16% clay content, a pH of 8.0, an organic matter content of 0.6%, electrical conductivity measuring 0.53 dS m^{-1}, and nutrient levels of approximately 400 ppm nitrogen (N), 6 ppm phosphorus (P), and 159 ppm potassium (K).

2.2. Experimental Design

The experiment followed a randomized complete block design, with three replications per treatment and a net plot size of 8.0 m × 2.2 m. The study encompassed five distinct weed control treatments (Table 1). Herbicides employed in the study were pendimethalin (applied at 1.65 kg a.i. ha^{-1}) and bromoxynil (applied at 0.30 kg a.i. ha^{-1}). The application of herbicides was conducted using a knapsack sprayer equipped with a flat-fan nozzle, utilizing water as a carrier at a volume of 300 L ha^{-1}. For raising parthenium weed seedlings, seeds were collected from naturally occurring local populations and uniformly broadcasted in each experimental plot (approximately 10 g of seeds), excluding the weed-free treatment. Regular manual removal of weed species, aside from parthenium weed, was carried out in all treatments. The weed-free treatment was meticulously maintained, ensuring the absence of all weeds, including parthenium weed.

Table 1. Treatments employed to control parthenium weed in the study.

Treatments	Dose (kg a.i. ha^{-1})	Time of Application (Days after Sowing)
Weed-free		Kept weed-free throughout the crop season
Pendimethalin	1.65	3
Bromoxynil	0.30	22
Pendimethalin *followed by* Bromoxynil	1.65 *followed by* 0.30	3 *followed by* 22
Weedy		Weeds were not controlled throughout the crop season

2.3. Crop Management Practices

The field was irrigated through a soaking irrigation process, followed by two cultivations, and leveling to prepare a uniform seed bed. The seed of sorghum cultivar 'Lajawab', sourced from the Maize and Millets Research Institute in Sahiwal, Pakistan, was used in the study. Planting was conducted at a seed rate of 10 kg ha^{-1}, with rows spaced at 30 cm. Sowing was carried out using a manual seed drill in the second week of July in both years. Critical growth stages, including booting, panicle initiation, and the commencement of grain formation, were accompanied by irrigation. For fertilization, N and P were applied to the soil at rates of 80 kg ha^{-1} and 40 kg ha^{-1}, respectively, in the form of urea (46% N) and diammonium phosphate (46% P_2O_5). A complete dose of P and half of the N dose were applied at the sowing time. The remaining half of the N dose was split and applied at 25 and 50 days after sowing. Harvesting of the experiments was conducted in mid-October during both years.

2.4. Measurements and Observations

Various weed and crop growth and yield parameters were measured during the course of the study. Forty-five days after crop sowing, the density and biomass of parthenium weed were measured in each treatment plot by randomly selecting two locations within each plot, each measuring 1 m^2. The parthenium weed plants in each quadrat were counted, harvested just above the soil surface, and placed in paper bags. The dry biomass was recorded after drying in an oven at 70 °C for three days.

After 60 days of sowing, 5 sorghum plants were randomly harvested from each treatment plot by cutting just above the soil level. These plant samples were placed in paper bags and dried in an oven at 70 °C for three days to determine the dry biomass per plant. Additionally, the leaves of ten randomly chosen sorghum plants were collected to measure the leaf fresh weight per plant at the same growth stage. The height of ten plants per treatment plot was recorded just before harvest and averaged.

The number of grain heads was counted from two randomly selected locations within each treatment plot, each measuring 1 m^2, before harvesting the crop. After harvesting and threshing, a sub-sample of 1000 grains was randomly selected from each plot, weighed, and the average 1000-grain weight was recorded. The crop was harvested manually for each treatment plot. To avoid the edge effect, border two rows on each side of the plots were excluded from yield and related measurements. The heads were removed, dried, and threshed to record the grain yield. The above-ground vegetative biomass from the whole plot was weighed immediately after harvesting to record the fresh forage yield. Subsequently, it was left in the field for sun drying for three weeks and then weighed to record the dry fodder yield.

2.5. Statistical Analysis

The normality of the data distribution was checked using the PROC UNIVARIATE procedure which determined that no transformations were required for any parameter except weed density. Data from both years underwent analysis of variance (ANOVA), revealing a significant effect of the year ($p < 0.05$) for most crop parameters. Consequently, data for these parameters from both years were analyzed separately utilizing Statistix-8.1 software. However, for parthenium weed density ($p = 0.36$) and dry biomass ($p = 0.90$), the effect of the year was deemed non-significant. Therefore, data for these parameters from both years were pooled before analysis. The ANOVA was conducted using a randomized complete block design, and treatment means were differentiated using the least significant difference (LSD) test at $p < 0.05$.

Before analysis, the weed density data were transformed using a square-root transformation [$\sqrt{}(x + 0.5)$] to improve their distribution normality. Weed control efficiency was calculated utilizing the following equation:

$$\text{Weed control efficiency (\%)} = B_W - B_T/B_W \times 100 \quad (1)$$

In Equation (1), B_W represents the parthenium weed biomass in the weedy treatment, and B_T represents the biomass in the respective weed control treatment. Graphs were created using Microsoft Excel, where treatment means, or percentage values were depicted along with the ± standard error of means. Additionally, relationships between parthenium weed density and biomass, as well as parthenium weed biomass and sorghum grain yield, were analyzed using correlation analysis in Microsoft Excel.

2.6. Economic Analysis

An economic analysis was carried out to calculate the net benefit of the various treatments as originally explained in CIMMYT [35] and modified and adopted for Pakistani conditions by Farooq and Nawaz [36]. The fixed costs encompassed charges for land lease and preparation, seed, irrigation, and fertilizers. On the other hand, variable costs included the cost of herbicides and charges related to herbicide application or weed removal. Net benefits (in USD per hectare) for each treatment were computed by deducting the total cost from the gross income. This economic analysis was conducted individually for each year using the treatment means.

3. Results

3.1. Weed Parameters

The density and biomass of parthenium weed did not vary across the two years of the study. All treatments demonstrated a significant effect ($p < 0.05$) on both the density and dry biomass of parthenium weed compared to the weedy control (Table 2). The weedy control exhibited the highest parthenium weed density and biomass, while the pendimethalin followed by (fb) bromoxynil application displayed the lowest density and biomass of parthenium weed (Table 2). A highly significant and positive correlation ($p < 0.001$; r = 0.93) was observed between the density and biomass of parthenium weed (Figure 1a).

Table 2. Effect of different weed control treatments on parthenium weed density and biomass in sorghum.

Weed Control Treatment	Parthenium Weed Density (m^{-2}) *	Parthenium Weed Dry Biomass ($g\ m^{-2}$)
Pendimethalin	3.9 (15.2) b	28.3 b
Bromoxynil	3.4 (10.8) c	22.7 b
Pendimethalin *fb* bromoxynil	2.3 (5.0) d	9.0 c
Weedy	4.8 (23.2) a	62.8 a
LSD ($p < 0.05$)	0.49	5.97

* The weed density data were transformed using a square-root transformation [$\sqrt{(x + 0.5)}$], and the original values are provided in parentheses. In columns where treatment means share the same case letter, there is no significant difference ($p < 0.05$) based on the LSD test.

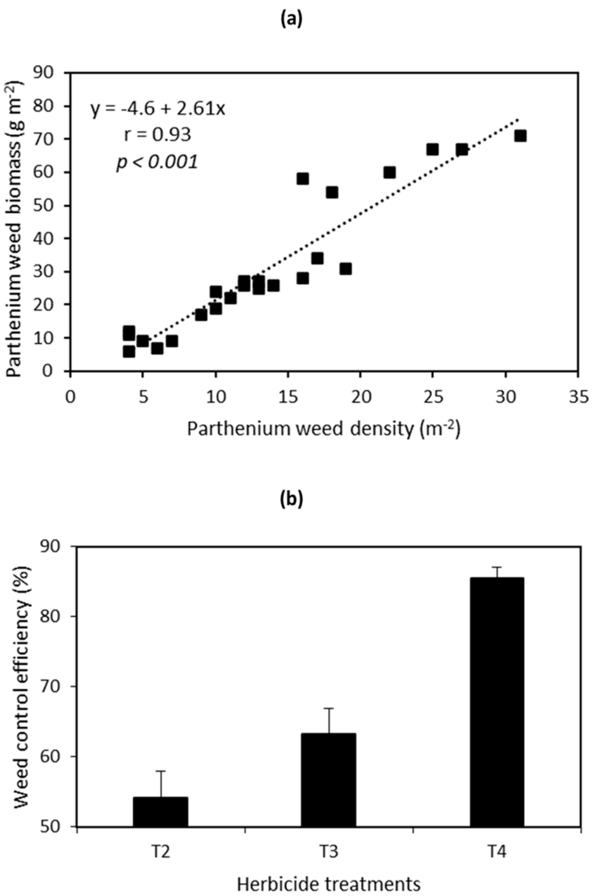

Figure 1. (**a**) Correlation between density and biomass of parthenium weed, and (**b**) weed control efficiency of various herbicide treatments in sorghum. Error bars depict the ± standard error of means. T2 = Pendimethalin, T3 = Bromoxynil, T4 = Pendimethalin followed by bromoxynil.

The weed control efficiency varied significantly across the experimental treatments (Figure 1b). The most efficient control (86%) was achieved with the pendimethalin fb bromoxynil treatment, while pendimethalin or bromoxynil applications individually resulted in only 54% and 63% weed control, respectively, compared to the weedy control (Figure 1b).

3.2. Sorghum Growth and Yield

The weed control treatments had a significant ($p < 0.05$) effect on sorghum growth, yield and yield-related traits during both years of the study (Tables 3 and 4). The leaf fresh weight per plant, plant dry biomass, plant height, and number of heads m^{-2}, fresh forage yield, dry fodder yield, 1000-grain weight, and grain yield were the highest in the weed-free treatment followed by pendimethalin fb bromoxynil treatment as compared to the weedy treatment (Tables 3 and 4). Pendimethalin treatment was the least effective among the weed control treatments in terms of sorghum growth and yield as compared to weedy treatment. The grain yield was significantly higher in weed-free (33 to 36%), pendimethalin fb bromoxynil (20 to 23%), bromoxynil (12 to 14%), and pendimethalin (6 to 9%) as compared to the weedy treatment during both years (Table 4). Sorghum grain yield was negatively correlated ($p < 0.001$; $r = -0.83$) with parthenium weed biomass (Figure 2).

Table 3. Effect of various weed control treatments on sorghum growth.

Weed Control Treatment	Leaf Fresh Weight Per Plant (g)		Plant Dry Biomass (g)		Plant Height (cm)		Number of Heads (m^{-2})	
	2016	2017	2016	2017	2016	2017	2016	2017
Weed-free	9.3 a	9.0 a	24.2 a	21.2 a	154.5 a	150.1 a	85.3 a	82.0 a
Pendimethalin	6.0 c	6.0 b	18.8 d	15.7 d	139.7 c	132.2 d	66.7 cd	62.0 d
Bromoxynil	6.3 c	6.0 b	20.1 c	17.3 c	143.6 bc	136.2 c	70.7 c	66.0 c
Pendimethalin *fb* bromoxynil	7.7 b	7.7 a	22.1 b	19.1 b	145.7 b	138.0 b	77.3 b	72.0 b
Weedy	5.3 c	5.7 b	18.3 e	15.4 e	134.9 d	128.3 e	64.0 d	58.3 e
LSD ($p < 0.05$)	1.14	1.57	0.44	0.25	4.50	0.48	4.51	2.89

In columns where treatment means share the same case letter, there is no significant difference ($p < 0.05$) based on the LSD test.

Table 4. Effect of various weed control treatments on sorghum yield and the related traits.

Weed Control Treatment	Fresh Forage Yield (t ha^{-1})		Dry Fodder Yield (t ha^{-1})		1000-Grain Weight (g)		Grain Yield (t ha^{-1})	
	2016	2017	2016	2017	2016	2017	2016	2017
Weed-free	23.1 a	21.2 a	15.4 a	15.0 a	23.0 a	21.0 a	1.15 a	1.14 a
Pendimethalin	18.1 d	16.1 d	8.9 c	7.5 c	20.0 d	17.8 d	0.82 c	0.80 d
Bromoxynil	18.9 c	17.0 c	9.5 bc	8.2 bc	20.8 c	18.7 c	0.88 c	0.85 c
Pendimethalin *fb* bromoxynil	21.1 b	19.2 b	11.6 b	10.3 b	21.8 b	19.8 b	0.96 b	0.95 b
Weedy	17.6 d	15.6 e	8.3 c	7.0 c	19.5 e	17.4 e	0.77 d	0.73 e
LSD ($p < 0.05$)	0.49	0.45	1.08	0.91	0.32	0.23	0.05	0.04

In columns where treatment means share the same case letter, there is no significant difference ($p < 0.05$) based on the LSD test.

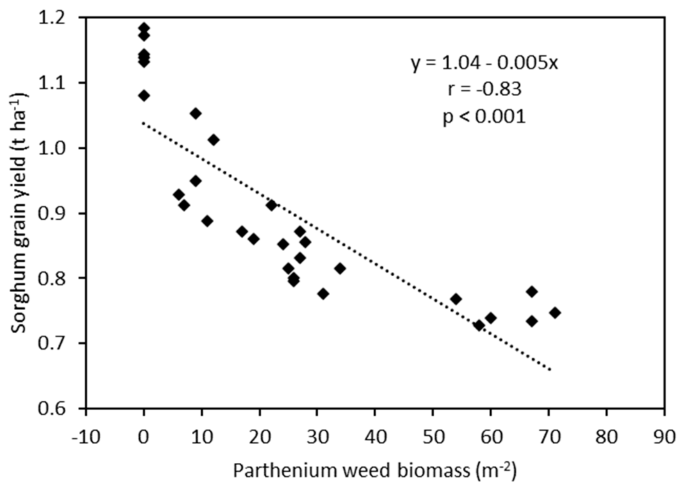

Figure 2. The correlation between parthenium weed biomass and sorghum grain yield.

3.3. Economics

The economic analysis revealed that effective control of parthenium weed increased the net benefits and benefit-cost ratio (Table 5). The benefits were the highest in the weed-free treatment followed by the pendimethalin fb bromoxynil treatment during both years (Table 5). Weedy control was the least beneficial treatment from an economics point of view.

Table 5. Economic indicators of various weed control treatments in sorghum.

Weed Control Treatments	Gross Income (USD)	Fixed Cost (USD ha^{-1})	Variable Cost (USD ha^{-1})	Total Cost (USD ha^{-1})	Net Benefit (USD ha^{-1})	Benefit Cost Ratio
			2016			
Weed-free	727	361	55	416	310	1.75
Pendimethalin	508	361	17	378	129	1.34
Bromoxynil	545	361	12	374	171	1.46
Pendimethalin *fb* bromoxynil	600	361	29	391	210	1.54
Weedy	476	361	0	361	115	1.32
			2017			
Weed-free	719	361	55	416	303	1.73
Pendimethalin	489	361	17	378	111	1.29
Bromoxynil	521	361	12	374	147	1.39
Pendimethalin *fb* bromoxynil	588	361	29	391	197	1.51
Weedy	447	361	0	361	86	1.24

The amounts are in USD (1 USD = 110.7 Pakistani Rupees as per conversion rate at the time of the completion of the study, i.e., February 2017). Calculations are made on the mean values.

4. Discussion

These results clearly show that parthenium weed interfered strongly with grain sorghum growth and resulted in significant yield loss when uncontrolled. All the herbicides reduced the weed density and biomass compared to the weedy control. However, only the sequential application of pendimethalin (pre-emergence) and bromoxynil (post-emergence) proved effective in controlling parthenium weed in sorghum (86% control). The sole application of either herbicide could achieve partial control (54 to 63%). Weed control improved sorghum crop growth and ultimately its grain yield. Sorghum growth suppression and yield reduction in the weedy treatment were due to strong interference (re-source competition and allelopathic effect) of parthenium weed with sorghum [15,37]. Parthenium weed could emerge along with the crop and compete for nutrients and moisture strongly. At early growth stages, the release of allelochemicals into the rhizosphere by this weed species might have also suppressed crop growth [11].

The sole application of pendimethalin was not effective in controlling parthenium weed probably because it had less residual effect on parthenium weed seedlings which emerged sometime after crop emergence. Pendimethalin acts as a root growth inhibitor and helps in controlling the early stages of weed growth, especially before they emerge from the soil. Normally, pendimethalin is quite effective in controlling both grassy and broadleaf weed species during their early growth stages, primarily owing to its residual effects [29]. However, variable results for this herbicide on parthenium weed control have been reported in the past. For example, Tadesse et al. [26] reported ineffective control of parthenium weed by a pre-emergence application of pendimethalin in a grain sorghum crop intercropped with a cowpea crop. In another study, Tamado and Milberg [25] reported insufficient control of parthenium weed in grain sorghum by a single application of the herbicide 2,4-D. It is possibly due to the protracted germination behaviour of parthenium weed [10]. Parthenium seeds can stay viable in the seedbank for a long time and may germinate quickly when the moisture is sufficient [13]. Moreover, low soil moisture under arid environment and high temperature during this study might also have reduced the efficacy of pendimethalin [38]. Therefore, a post-emergence herbicide is deemed necessary to control parthenium weed effectively.

On the other hand, bromoxynil alone applied post-emergence, also provided insufficient control of parthenium weed. Rosales-Robles et al. [32] reported that bromoxynil provided good control of broadleaf weed species in grain sorghum but only when there was sufficient rainfall. It is also possible that bromoxynil alone is generally less effective against parthenium weed as in previous studies, it performed well against broadleaf weeds in grain sorghum when combined (pre-mix or tank-mix) with pyrasulfotole [33,34]. It was suggested that the synergistic action of bromoxynil and pyrasulfotole had high efficacy against most of the broadleaf weed species.

The combined, layered application of pre- and post-emergence herbicides has proven to be highly effective in controlling parthenium weed compared to using either herbicide individually. This effectiveness stems from the fact that post-emergence herbicides are designed to eliminate weeds that sprout after the application of pre-emergence herbicides like pendimethalin. Singh et al. [39] demonstrated that applying pendimethalin pre-emergence followed by a post-emergence application of 2,4-D plus atrazine resulted in excellent weed control and increased grain yield in sorghum. Similarly, in another study, applying S-metolachlor pre-emergence followed by post-emergence herbicides bromoxynil plus pyrasulfotole or atrazine provided over 80% control of problematic weeds like Palmer amaranth (*Amaranthus palmeri* S. Wats.) and green foxtail [*Setaria viridis* (L.) Beauv.] in grain sorghum [38]. However, using pre- or post-emergence herbicides alone did not yield satisfactory weed control [40]. In the present study, the strategic combination of a root growth inhibitor (pendimethalin) along with a photosystem II inhibitor (bromoxynil) proved highly effective in controlling parthenium weed. This robust weed control led to reduced weed-crop competition, ultimately benefiting the growth and yield of sorghum.

5. Conclusions

Parthenium weed caused a substantial loss in sorghum yield in the weedy treatment over that observed for the weed-free treatment during two years of the study. Different weed control treatments had differential effects with the sole application of pendimethalin and bromoxynil being not so effective (54% and 63% control over the weedy treatment) in controlling parthenium weed. Combined use of pre-emergence (pendimethalin) and post-emergence (bromoxynil) herbicides provided effective control (86%). Therefore, a recommended approach for effective control of parthenium weed and achieving higher yields of grain sorghum involves a sequential application of these two herbicides. This is a suitable chemical control program for parthenium weed in grain sorghum crops grown under arid conditions in Pakistan and in areas with similar climatic conditions. This manuscript is a valuable contribution to the protection of sorghum against weeds in arid conditions and has great potential for practical importance.

Author Contributions: Conceptualization and methodology, A.A.B., M.F., B.S.C. and S.A.; experiment conduction and data curation, A.A.B. and A.N.; data analysis and writing—original draft preparation, A.A.B.; writing—review and editing, A.A.B., A.N., M.F., B.S.C. and S.A.; supervision and resource acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The University of Queensland, Australia and the Australian Government.

Data Availability Statement: All the data are included within this manuscript. The raw data and related information are available to the relevant parties upon written request to the corresponding author.

Acknowledgments: Authors acknowledge the project support from The University of Queensland, Australia and the Australian Government. Authors are thankful to the technical staff at the Research Farm of Bahauddin Zakariya University, Layyah campus, Pakistan for their support in conducting this study. Authors are also thankful to their respective institutes for their ongoing support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Habib, N.; Tahir, A.; Ain, Q. Current situation and future outlook of sorghum area and production in Pakistan. *Asian J. Agric. Rur. Dev.* **2013**, *3*, 283–289.
2. Hussain, N.; Baloch, M.S.; Yousaf, M.; Naeem, M.; Khakwani, A.A.; Begum, I. Performance of sorghum varieties in Potohar region. *Gomal Uni. J. Res.* **2011**, *27*, 26–30.
3. Ghani, A.; Saeed, M.; Hussain, D.; Arshad, M.; Shafique, M.M.; Shah, S.A.S. Evaluation of different sorghum (*Sorghum bicolor* L. Moench) varieties for grain yield and related characteristics. *Sci. Lett.* **2015**, *3*, 72–74.
4. Bajwa, A.A.; Chauhan, B.S.; Farooq, M.; Shabbir, A.; Adkins, S.W. What do we really know about alien plant invasion? a review of the invasion mechanism of one of the world's worst weeds. *Planta* **2016**, *244*, 39–57. [CrossRef]
5. Bajwa, A.A.; Farooq, M.; Nawaz, A.; Yadav, L.; Chauhan, B.S.; Adkins, S. Impact of invasive plant species on the livelihoods of farming households: Evidence from *Parthenium hysterophorus* invasion in rural Punjab, Pakistan. *Biol. Invasions* **2019**, *21*, 3285–3304. [CrossRef]
6. Bajwa, A.A.; Nguyen, T.; Navie, S.; O'Donnell, C.; Adkins, S. Weed seed spread and its prevention: The role of roadside wash down. *J. Environ. Manag.* **2018**, *208*, 8–14. [CrossRef] [PubMed]
7. Tamado, T.; Milberg, P. Weed flora in arable fields of eastern Ethiopia with emphasis on the occurrence of *Parthenium hysterophorus*. *Weed Res.* **2000**, *40*, 507–521. [CrossRef]
8. Asif, M.; Ayub, M.; Tanveer, A.; Akhtar, J. Estimating yield losses and economic threshold level of *Parthenium hysterophorus* in forage sorghum. *Planta Danin.* **2017**, *35*, e017164158. [CrossRef]
9. Bajwa, A.A.; Chauhan, B.S.; Adkins, S. Morphological, physiological and biochemical responses of two Australian biotypes of *Parthenium hysterophorus* to different soil moisture regimes. *Environ. Sci. Pollut. Res.* **2017**, *24*, 16186–16194. [CrossRef]
10. Bajwa, A.A.; Chauhan, B.S.; Adkins, S.W. Germination ecology of two Australian biotypes of ragweed parthenium (*Parthenium hysterophorus*) relates to their invasiveness. *Weed Sci.* **2018**, *66*, 62–70. [CrossRef]
11. Singh, H.P.; Batish, D.R.; Pandher, J.K.; Kohli, R.K. Assessment of allelopathic properties of *Parthenium hysterophorus* residues. *Agric. Ecosyst. Environ.* **2003**, *95*, 537–541. [CrossRef]
12. Nguyen, T.; Bajwa, A.A.; Navie, S.; O'Donnell, C.; Adkins, S. Parthenium weed (*Parthenium hysterophorus* L.) and climate change: The effect of CO2 concentration, temperature, and water deficit on growth and reproduction of two biotypes. *Environ. Sci. Pollut. Res.* **2017**, *24*, 10727–10739. [CrossRef] [PubMed]
13. Nguyen, T.; Bajwa, A.A.; Navie, S.; O'Donnell, C.; Adkins, S. The soil seedbank of pasture communities in central Queensland invaded by *Parthenium hysterophorus* L. *Range. Ecol. Manag.* **2017**, *70*, 244–254. [CrossRef]
14. Bajwa, A.A.; Weston, P.A.; Gurusinghe, S.; Latif, S.; Adkins, S.W.; Weston, L.A. Toxic potential and metabolic profiling of two Australian biotypes of the invasive plant parthenium weed (*Parthenium hysterophorus* L.). *Toxins* **2020**, *12*, 447. [CrossRef] [PubMed]
15. Tamado, T.; Ohlander, L.; Milberg, P. Interference by the weed *Parthenium hysterophorus* L. with grain sorghum: Influence of weed density and duration of competition. *Int. J. Pest Manag.* **2002**, *48*, 183–188. [CrossRef]
16. Safdar, M.E.; Tanveer, A.; Khaliq, A.; Maqbool, R. Critical competition period of parthenium weed (*Parthenium hysterophorus* L.) in maize. *Crop Prot.* **2016**, *80*, 101–107. [CrossRef]

17. Bajwa, A.A.; Ullah, A.; Farooq, M.; Chauhan, B.S.; Adkins, S. Effect of different densities of parthenium weed (*Parthenium hysterophorus* L.) on the performance of direct-seeded rice under aerobic conditions. *Arch. Agron. Soil Sci.* **2019**, *65*, 796–808. [CrossRef]
18. Bajwa, A.A.; Ullah, A.; Farooq, M.; Chauhan, B.S.; Adkins, S. Competition dynamics of *Parthenium hysterophorus* in direct-seeded aerobic rice fields. *Exp. Agric.* **2020**, *56*, 195–203. [CrossRef]
19. Bajwa, A.A.; Nawaz, A.; Farooq, M.; Chauhan, B.S.; Adkins, S. Parthenium weed (*Parthenium hysterophorus*) competition with grain sorghum under arid conditions. *Exp. Agric.* **2020**, *56*, 387–396. [CrossRef]
20. Shabbir, A.; Bajwa, A.A.; Dhileepan, K.; Zalucki, M.; Khan, N.; Adkins, S. Integrated use of biological approaches provides effective control of parthenium weed. *Arch. Agron. Soil Sci.* **2018**, *64*, 1861–1878. [CrossRef]
21. Belgeri, A.; Bajwa, A.A.; Shabbir, A.; Navie, S.; Vivian-Smith, G.; Adkins, S. Managing an invasive weed species, *Parthenium hysterophorus*, with suppressive plant species in Australian grasslands. *Plants* **2020**, *9*, 1587. [CrossRef] [PubMed]
22. Singh, S.; Yadav, A.; Balyan, R.S.; Malik, R.K.; Singh, M. Control of ragweed parthenium (*Parthenium hysterophorus*) and associated weeds. *Weed Technol.* **2004**, *18*, 658–664. [CrossRef]
23. Odero, D.C. Response of ragweed parthenium (*Parthenium hysterophorus*) to saflufenacil and glyphosate. *Weed Technol.* **2012**, *26*, 443–448. [CrossRef]
24. Fernandez, J.V.; Odero, D.C.; MacDonald, G.E.; Ferrell, J. *Parthenium hysterophorus* L. control in response to pyraflufen-ethyl application. *Crop Prot.* **2014**, *57*, 35–37. [CrossRef]
25. Tamado, T.; Milberg, P. Control of Parthenium (*Parthenium hysterophorus*) in grain sorghum (*Sorghum bicolor*) in the smallholder farming system in eastern Ethiopia. *Weed Technol.* **2004**, *18*, 100–105. [CrossRef]
26. Tadesse, B.; Das, T.K.; Yaduraju, N.T. Effects of some integrated management options on parthenium interference in sorghum. *Weed Biol. Manag.* **2010**, *10*, 160–169. [CrossRef]
27. Rehman, A.; Hassan, F.U.; Qamar, R.; Ali, M.; Zamir, M.S.; Iqbal, S.; Masood, N.; Javeed, H.M.R. Efficacy of herbicides in controlling *Parthenium hysterophorus* L. in spring maize (*Zea mays* L.). *Qual. Ass. Saf. Crops Foods* **2017**, *9*, 213–220. [CrossRef]
28. Nishanthan, K.; Sivachandiran, S.; Marambe, B. Seedbank dynamics and integrated management of *Parthenium hysterophorus* in vegetable capsicum. *Crop Prot.* **2018**, *107*, 56–63. [CrossRef]
29. Bajwa, A.A.; Ullah, A.; Farooq, M.; Chauhan, B.S.; Adkins, S. Chemical control of parthenium weed (*Parthenium hysterophorus* L.) in two contrasting cultivars of rice under direct-seeded conditions. *Crop Prot.* **2019**, *117*, 26–36. [CrossRef]
30. Dantata, I.J.; Shittu, E.A. Effect of pendimethalin on relative tolerance of sorghum in northern Guinea Savanna areas of Nigeria. *Asian J. Agric. Food Sci.* **2014**, *2*, 221–226.
31. Tadesse, B. Studies on Integrated Management of Weeds in Sorghum with Special Emphasis on *Parthenium hysterophorus* L. Master's Thesis, Indian Agricultural Research Institute, New Delhi, India, 2001.
32. Rosales-Robles, E.; Sanchez-de-la-Cruz, R.; Salinas-Garcia, J.; Pecina-Quintero, V. Broadleaf weed management in grain sorghum with reduced rates of postemergence herbicides. *Weed Technol.* **2005**, *19*, 385–390. [CrossRef]
33. Fromme, D.D.; Dotray, P.A.; Grichar, W.J.; Fernandez, C.J. Weed control and grain sorghum (*Sorghum bicolor*) tolerance to pyrasulfotole plus bromoxynil. *Int. J. Agron.* **2012**, *2012*, 951454. [CrossRef]
34. Reddy, S.S.; Stahlman, P.W.; Geier, P.W.; Thompson, C.R.; Currie, R.S.; Schlegel, A.J.; Olson, B.L.; Lally, N.G. Weed control and crop safety with premixed pyrasulfotole and bromoxynil in grain sorghum. *Weed Technol.* **2013**, *27*, 664–670. [CrossRef]
35. CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo). *From Agronomic Data to Farmers Recommendations: An Economics Training Manual*; CIMMYT: Mexico City, Mexico, 1988; pp. 31–33.
36. Farooq, M.; Nawaz, A. Weed dynamics and productivity of wheat in conventional and conservation rice-based cropping systems. *Soil Till. Res.* **2014**, *141*, 1–9. [CrossRef]
37. Belz, R.G.; Reinhardt, C.F.; Foxcroft, L.C.; Hurle, K. Residue allelopathy in *Parthenium hysterophorus* L.-does parthenin play a leading role? *Crop Prot.* **2007**, *26*, 237–245. [CrossRef]
38. Jursik, M.; Soukup, J.; Holec, J.; Andr, J.; Hamouzová, K. Efficacy and selectivity of pre-emergent sunflower herbicides under different soil moisture conditions. *Plant Prot. Sci.* **2015**, *51*, 214–222. [CrossRef]
39. Singh, G.; Muker, H.S.; Singh, G.; Singh, A.; Singh, A. Effect of chemical weed management on growth and yield attributes of kharif sorghum (*Sorghum bicolor* L.). *Int. J. Curr. Micro. App. Sci.* **2018**, *7*, 2072–2077. [CrossRef]
40. Currie, R.; Geier, P. Weed control and crop injury with single or sequential herbicide applications in grain sorghum. *Kans. Agric. Exp. Stn. Res. Rep.* **2016**, *2*, 26. [CrossRef]