

Research Article

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Keywords:

Alternative crop; semi-arid; soil; tolerance; weeds


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Impact of soil-residual herbicides on industrial hemp (*Cannabis sativa*) phytotoxicity and biomass yield in west Texas

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Abstract

Industrial hemp is a multipurpose crop cultivated for fiber, seed, human food, and animal feed. Hemp legalization in Texas creates a considerable potential to increase its acreage in semi-arid conditions; however, knowledge is limited on growing hemp optimally in Texas. Best management practices, including weed control, require evaluation for profitable hemp production. As little is known about the herbicide tolerance of hemp, field studies were conducted to test several soil-residual herbicides with different modes of action for phytotoxicity to two hemp cultivars, ‘Yuma’ and ‘Jinma’. The experimental units were randomized three times in a blocked split-plot design with hemp cultivars in the main plots and soil-residual herbicides in the subplots. Ethalfluralin, the mixture of sulfentrazone and S-metolachlor, prometryn, and S-metolachlor, resulted in 60% to 90% and 73% to 100% weed control as compared to the nontreated control in 2021 and 2022, respectively. The highest hemp germination, stand count, and plant height were observed with ethalfluralin and S-metolachlor herbicides; however, no significant differences were observed for hemp germination and plant height compared to the nontreated control. S-metolachlor, ethalfluralin, fomesafen, and prometryn resulted in similar hemp biomass compared to the nontreated control. Overall, the results indicate that hemp is tolerant to ethalfluralin, prometryn, and S-metolachlor, and these soil-residual herbicides were effective for weed control in hemp. The mixture of bicyclopyrone plus S-metolachlor, metribuzin plus S-metolachlor, and mesotrione should be avoided, as they caused significant injury to hemp plants. Future research is needed to test the efficacy of different preemergence and postemergence herbicides that can be used in industrial hemp grown under different environments, making sure the delta-9-tetrahydrocannabinol content of the hemp is below the legal content restrictions.

Introduction

Industrial hemp is an annual crop produced for fibers and seeds, and is estimated to be grown in more than 30 countries worldwide (Crini et al. 2020). China is the largest hemp producer and exporter, whereas Europe and Canada also play an essential role in hemp production (Crini et al. 2020). In addition to nine major submarkets, including textiles, agriculture, automotive, food and beverage, paper, furniture, construction, recycling, and personal care, more than 25,000 items are made from industrial hemp (Crini et al. 2020; Figueiredo et al. 2010; Fike 2016; Thomas et al. 2011). According to an analysis by Johnson (2018), the United States accounted for \$600 million in sales of hemp-based products in 2017. Texas recently legalized hemp production in 2019, and most farming areas are in West Texas (Moore 2020). West Texas has a semi-arid climate; that is, it includes the areas that are not completely dry and receive a little rain. This part of Texas receives 469 mm of annual rainfall compared to potential evapotranspiration of 1,501 mm (Bhattarai et al. 2020; Dhakal et al. 2019; TAMU 2021). In such a water-limited production system, introducing a new alternative crop, such as industrial hemp, creates challenges and opportunities (Moore 2020). Researchers focus on understanding the agronomic practices and environmental conditions favorable for profitable hemp production (Johnson 2018; Sunoj Valiaparambil Sebastian et al. 2023), and the interest in cultivating the crop is increasing in the semi-arid West Texas (Moore 2020).

Weeds are a major problem in agriculture, competing with the primary crop for space, light, water, and nutrients (Sandler and Gibson 2019). Therefore, weed control is essential for



Table 1. Herbicides tested in industrial hemp in 2021 and 2022 at Quaker Research Farm, Texas Tech University, Lubbock, TX

Year of application		Active ingredient	Product	Rate	Group	Manufacturer
2021	2022	Ethalfuralin	Sonalan	0.84	3	Gowan Company
2021	–	Bicyclopyrone, mesotrione, S-metolachlor	Acuron Flexi	1.14	15, 27	Syngenta
2021	–	S-metolachlor, metribuzin	Boundary	1.37	15, 2	Syngenta
2021	2022	Sulfentrazone, S-metolachlor	Broad Axe	0.25	14, 15	Syngenta
2021	2022	Fomesafen	Reflex	0.21	14	Syngenta
2021	–	Mesotrione	Callisto	0.14	27	Syngenta
2021	2022	Prometryn	Caparol	0.9	5	Syngenta
2021	2022	S-metolachlor	Dual magnum	1.39	15	Syngenta

successful crop production, although labor- and time-intensive. Reports suggest weeds can severely affect hemp germination and plant population (Sandler and Gibson 2019). There is a lack of understanding of effective weed control in industrial hemp production, as hemp cultivation is a comparatively new practice for U.S. farmers (Sandler and Gibson 2019). It has been observed that once hemp plants are established, they can suppress weeds because of their rapid canopy closure (Cherney and Small 2016). Cultural and mechanical weed control practices could be sustainable in some production systems, but these are time-consuming and do not fit all situations (Byrd 2019; Ortmeier-Clarke et al. 2022). Chemical weed control is a more practical and economical method for crops when cultural and mechanical practices are not feasible (Maxwell 2016). Although hemp has gained popularity as a high-value crop in the United States, leading to a significant increase in farm production (Cherney and Small 2016; Ortmeier-Clarke et al. 2022), there are still no herbicides recommended in the United States to control the weeds that complicate hemp production (Sandler and Gibson 2019). Because hemp was federally legalized in the United States with the passage of the 2018 farm bill. The U.S. Department of Agriculture and the Environmental Protection Agency have been working to establish hemp production guidelines, including the use of herbicides. Regulatory approval for herbicides involves a thorough evaluation process by government agencies to ensure product safety, efficacy, and environmental impact. Although Canada has registered quizalofop-P-ethyl and ethalfuralin, China has registered S-metolachlor, pendimethalin, and acetochlor for weed control in hemp (Ortmeier-Clarke et al. 2022). This allows herbicides with a similar mode of action to receive motivation in legal registration procedures and potential use in hemp cultivation in the United States.

A few researchers provide an understanding of how hemp responds to various herbicides, but there is still no documented research on how different hemp cultivars may react to different soil-residual herbicides in the semi-arid West Texas environment. Evaluation of hemp response to different soil-residual herbicides is essential to provide information on herbicide registration for hemp in the region. Furthermore, no herbicides have been registered to be used in industrial hemp in the United States. Therefore, the objective of this study was to assess the effect of commonly used soil-residual herbicides in cotton (*Gossypium hirsutum* L.) and corn (*Zea mays* L.) on industrial hemp phytotoxicity under field conditions of West Texas. It was hypothesized that there would be no significant difference on hemp phytotoxicity and biomass yield when subjected to selected herbicide treatments compared with the nontreated control.

Materials and Methods

Experimental Site

A 2-yr field study was conducted during the summers of 2021 and 2022 at Quaker Research Farm of Texas Tech University, Lubbock, TX (33.58° N, 101.85° W, and 992 m above sea level). The climate of the experimental site is semi-arid, with average annual high and low temperatures of 23.3 C and 7.8 C, respectively (TAMU 2021). The soil of the experimental site comprised Amarillo sandy clay loam with a particle size distribution of 73.21% sand, 10.07% silt, and 16.72% clay in 0–10 cm soil depth (Parkash et al. 2021).

Cultivation Practices and Planting

Seedbeds were prepared with a tractor-mounted disc plow. Two hemp cultivars, ‘Yuma’ and ‘Jinma’, which are mainly grown for fiber production, were used for this experiment. Seeds were planted at 1.5 cm depth using a four-row planter at the rate of 28 kg ha⁻¹, maintaining a 100-cm spacing between the rows. Planting occurred on May 10 and April 19 in 2021 and 2022, respectively. The irrigation was supplied through a subsurface drip irrigation system. Pre-season irrigation was applied to moisten the soil before planting. Although hemp plants tolerate water stress, they need 300 mm of water throughout the growing season (Mettler 2021). Crop evapotranspiration (ET_c) was calculated based on the Penman-Monteith equation, and irrigation was applied to fully replace the crop water demand to avoid any water stress on the crop. The irrigation event was adjusted according to the rainfall events. Fertilizer was applied through fertigation at 90 kg ha⁻¹ N based on the recommendation of soil nutrient analysis.

Experimental Design

In both years, a split-plot design was set up with two hemp cultivars, ‘Yuma’ and ‘Jinma’, in main plots and soil-residual herbicides in the subplots. Eight soil-residual herbicides with varying modes of action were tested in 2021, and five soil-residual herbicides were tested in 2022 (Table 1). The herbicides tested in this study were widely available and used in previous studies on cotton and corn. The herbicides chosen in 2022 were based on the performance results in 2021. The herbicides that proved highly toxic to hemp plants in 2021 were excluded in 2022. Nontreated control plots were included to make comparisons. The experimental units were replicated three times, accounting for 54 plots in 2021 and 36 in 2022, respectively. The plot size was 6 m in length and 4 m in width; each plot had four rows. An alley space of 1.5 m was maintained to separate plots throughout the row length. Herbicides were applied immediately after planting using

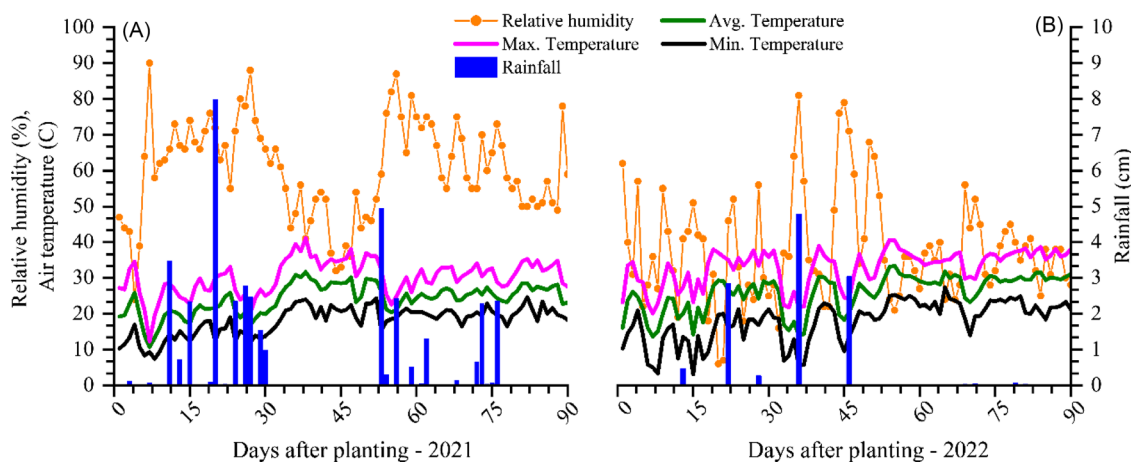


Figure 1. Daily rainfall events, average relative humidity, and minimum, maximum, and average air temperature observed during the growing seasons of 2021 (A) and 2022 (B) at the experimental site in Lubbock, TX.

a CO₂-pressurized handheld sprayer with a no. 4 nozzle (TeeJet XR11002-VS) on 46-cm spacing.

Data Collection

Hemp germination was recorded 7 d after planting (DAP) in both years based on a scale of 0 (no weed control or hemp injury) to 100 (complete weed control or hemp death). The hemp germination percentage was calculated using the number of germinated seeds over the total number of seeds planted in a plot multiplied by 100. Weed density at 30 and 60 DAP was recorded by counting all the weeds in the 0.50-m² quadrat in both years. The quadrat was randomly placed at four locations in each plot, and all the weeds were counted.

The hemp stand count was determined at 30 DAP by counting live hemp plants in a 1-m² area in each plot in both years. Hemp plant height was recorded at 30 DAP and before harvest (100 DAP) in 2021 and at 60 DAP and before harvest (100 DAP) in 2022, respectively, using a marked ruler scale to record the growth progress of the plants. Aboveground dry hemp biomass yield was calculated by harvesting 1 m² aboveground biomass area per plot using secateurs. The biomass was dried at 60 C for 48 h in an oven and then weighed on a calibrated scale.

Statistical Analysis

The data were analyzed using ANOVA with a split-plot design in R-studio version 3.5.2 using Agricolae package version 1.2-8 (De Mendiburu 2017). Data analysis was done separately for both years because some herbicides were used in 2021 but not in 2022, and the results in the 2-yr study were not similar; hence, data pooling was difficult to conduct. The parameter values in the tables and figures represent the mean values for cultivars and herbicide treatments. The treatment means were compared using the Fisher's protected LSD test at a significance level of $P \leq 0.05$. The mean separation was done only if the treatment had a significant P-value in the ANOVA table. Figures were prepared using OriginPro software version 2018b (Originlab Corp., Northampton, MA).

Results and Discussion

Weather Conditions

The weather data from on-site weather station included maximum, minimum, and average air temperature, relative humidity, and

rainfall events during two growing seasons (Figure 1). The daily average air temperature varied between 10.7 C and 31.8 C in 2021 and between 13.6 C and 33.4 C in 2022. The daily average maximum air temperature ranged between 12.3 C and 41.2 C in 2021 and 20.1 C and 40.7 C in 2022. The daily average minimum air temperature varied between 3.1 C and 27.4 C in 2021 and 7.4 C and 24.6 C in 2022. The daily average relative humidity ranged from 24.2% to 90.3% in 2021 and 6.4% to 81.3% in 2022. The total rainfall received during the 2021 growing season was considerably higher (391 mm) compared to the 2022 growing season (115 mm).

There was no significant difference between cultivars 'Yuma' and 'Jinma' on parameters measured in both years. There was no interaction of soil-residual herbicides and cultivars on the parameter measured, and the results are discussed for soil-residual herbicide effects only.

Influence of Soil-Residual Herbicides on Hemp Germination and Stand Count

In 2021, all the soil-residual herbicide treatments had a similar hemp germination percentage compared to the nontreated control (Table 2). However, hemp germination percentage differed significantly for herbicide treatments in 2022. Ethalfluralin had hemp germination (94.2%) success similar to that of the control (92.5%), which was also similar to the mixture of sulfentrazone plus S-metolachlor (85.2%) and S-metolachlor alone (88.3%). However, fomesafen (78.6%) and prometryn (78.3%) herbicides significantly reduced the hemp germination percentage in 2022 relative to the control. A previous greenhouse study on preemergence herbicides also showed a significant reduction in hemp emergence in ethofumesate, acetochlor, and pyroxasulfone treatments compared to nontreated control (Mettler 2021). In another study, S-metolachlor, diuron, linuron, pendimethalin, and acetochlor did not affect hemp emergence and performed similarly to nontreated control (Byrd 2019). All these aforementioned studies were conducted in different environments and soil types. Therefore, it appears that the sensitivity at the germination stage depends on the environment and the soil types to which seeds are exposed (Varga et al. 2022). Both hemp cultivars had no significant difference in germination in both years. Germination is a complex process that is influenced by various factors, and hence it is difficult to predict the precise impact of herbicides at this stage.

Table 2. Effect of soil-residual herbicides on hemp germination in 2021 and 2022 at the experimental site in Lubbock, TX^{a,b}

Treatments	Hemp germination	
	7 DAP	
	2021	2022
Cultivars (C)	%	
'Yuma'	94.3 a	90.1 a
'Jinma'	94.5 a	92.3 a
Herbicide (H)		
Ethalfuralin	95.1 a	94.2 a
Bicyclopyrone plus S-metolachlor	93.4 a	–
Metribuzin plus S-metolachlor	94.2 a	–
Sulfentrazone plus S-metolachlor	94.9 a	85.2 ab
Fomesafen	97.0 a	78.6 b
Mesotrione	94.3 a	–
Prometryn	95.7 a	78.3 b
S-metolachlor	93.2 a	88.3 ab
Control	96.7 a	92.3 a
C × H	NS	NS

^aMean values followed by different lowercase letters in each column indicate a significant difference in treatments ($P \leq 0.05$, Fisher's protected LSD test).

^bAbbreviations: C × H, cultivar and herbicide interactions; NS, nonsignificant.

Table 3. Effect of soil-residual herbicides on hemp stand count in 2021 and 2022 at the experimental site in Lubbock, TX^{a,b}

Treatments	Hemp stand count	
	30 DAP	
	2021	2022
Cultivars (C)	Plants m ⁻²	
'Yuma'	23.2 a	49.6 a
'Jinma'	24.3 a	52.6 a
Herbicide (H)		
Ethalfuralin	27.1 a	67.2 a
Bicyclopyrone plus S-metolachlor	0	–
Metribuzin plus S-metolachlor	0	–
Sulfentrazone plus S-metolachlor	26.5 a	49.1 b
Fomesafen	24.2 a	46.4 b
Mesotrione	0	–
Prometryn	25.3 a	53.3 ab
S-metolachlor	25.5 a	52.8 ab
Control	24.2 a	47.3 b
C × H	NS	NS

^aMean values followed by different lowercase letters in each column indicate a significant difference in treatments ($P \leq 0.05$, Fisher's protected LSD test).

^bAbbreviations: C × H, cultivar and herbicide interactions; NS, nonsignificant. Zeros were excluded during the analysis.

Similar to germination results, there was no significant difference in hemp stand count for different herbicides and cultivars at 30 DAP in 2021, though three of these herbicide treatments, bicyclopyrone plus S-metolachlor, metribuzin plus S-metolachlor, and mesotrione alone killed hemp plants as a result of toxicity in the early stage, rendering a zero stand count (Table 3). In 2022, there was a significant difference in hemp stand count (Table 3). Ethalfuralin had the highest hemp stand count with 67 plants m⁻² and had no toxic effect on hemp plants, and fomesafen's toxicity to hemp resulted in the lowest stand count, i.e., 46 plants m⁻². The nontreated control also had the lowest stand count with 47 plants m⁻², possibly due to competition created by weeds left uncontrolled. In 2022, ethalfuralin, sulfentrazone plus S-metolachlor, prometryn, and S-metolachlor alone had 42%,

Table 4. Effect of soil-residual herbicides on hemp plant height in 2021 and 2022 at the experimental site in Lubbock, TX

Treatments	Plant height			
	2021		2022	
	30 DAP	100 DAP	60 DAP	100 DAP
Cultivars (C)	cm			
'Yuma'	13 a ^z	210 a	113 a	244 a
'Jinma'	13 a	204 a	111 a	240 a
Herbicide (H)				
Ethalfuralin	25 a	269 a	126 a	254 a
Bicyclopyrone plus S-metolachlor	–	–	–	–
Metribuzin plus S-metolachlor	–	–	–	–
Sulfentrazone plus S-metolachlor	20 ab	292 a	114 abc	254 a
Fomesafen	15 b	272 a	109 bc	247 a
Mesotrione	15 b	237 a	–	–
Prometryn	20 ab	269 a	109 bc	252 a
S-metolachlor	21 ab	276 a	119 ab	261 a
Control	18 ab	249 a	98 c	237 a
C × H	NS ^y	NS	NS	NS

^aMean values followed by different lowercase letters in each column indicate a significant difference in treatments ($P \leq 0.05$, Fisher's protected LSD test).

^yAbbreviations: C × H, cultivar and herbicide interactions; NS, nonsignificant.

3.8%, 12.6%, and 11.5% more stand count, respectively, compared to the control. In 2021, a combination of bicyclopyrone plus S-metolachlor, metribuzin plus S-metolachlor, and mesotrione alone killed hemp plants during the early stage, showing their toxic effect on the hemp crop. A previous study by Byrd (2019) showed that metribuzin significantly reduced the number of hemp plants; however, S-metolachlor did not reduce the number of plants significantly compared to the nontreated check.

Another study by Mettler (2021) revealed a complete loss of hemp plants under metribuzin herbicide treatments 25 d after emergence. Mesotrione also significantly reduced the hemp stand by 80%, whereas S-metolachlor alone only reduced the stand count by 12% (Mettler 2021). Taking the above references into account, the complete loss of plants in our experiment with the combination of bicyclopyrone plus S-metolachlor and metribuzin plus S-metolachlor was a result of the herbicides' toxicity on the hemp. This also suggests that S-metolachlor alone did not kill plants, as indicated in Table 3. Most of the herbicides promoted higher stand count compared to the control by reducing crop-weed competition for space, light, moisture, and nutrients during the early stage of the crops. Ethalfuralin, prometryn, and S-metolachlor had the highest plant stand count and exerted no toxicity on hemp plants. Therefore, these herbicides could be used in hemp. In China, Amaducci *et al.* (2014) suggested the use of 65% metolachlor emulsion (3 L ha⁻¹) or 30% pendimethalin EC (3 L ha⁻¹) as an enclosed treatment for hemp plants in Heilongjiang Province.

Similarly, Liu *et al.* (2010) recommended 96% metolachlor EC at a rate of 1,050 mL ha⁻¹ or 50% acetochlor EC at a rate of 750 mL ha⁻¹ in hemp fields in Hunan Province. These herbicides are comparatively safer for hemp plants because of their formulation and selective reactivity to the weeds rather than the hemp plants.

Effect of Soil-Residual Herbicides on Hemp Plant Height and Biomass

The plant height results in 2021 and 2022 suggest that few soil-residual herbicides reduced plant height during early-mid growth stages (Table 4). However, soil-residual herbicides did

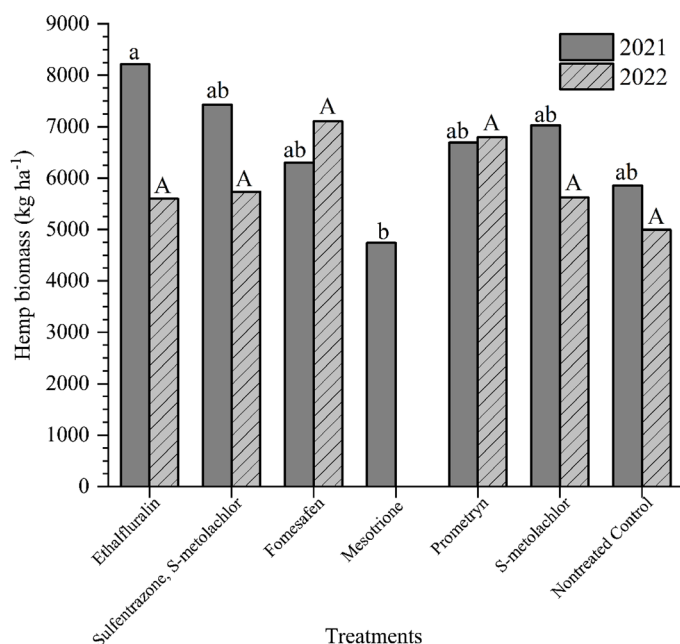


Figure 2. Effect of soil-residual herbicides on hemp biomass in 2021 and 2022 at the experimental site in Lubbock, TX. Bars with different lowercase and uppercase letters indicate a significant difference among treatments in 2021 and 2022, respectively ($P \leq 0.05$, Fisher's protected LSD test).

not affect the plant height at harvest during both the growing seasons. In 2021, fomesafen and mesotrione herbicides significantly reduced plant height at 30 DAP compared to ethalfluralin. In 2022, the plant height was significantly reduced in the nontreated control compared to soil-residual herbicide treatments such as ethalfluralin and S-metolachlor at 60 DAP. Also, fomesafen and prometryn significantly reduced the hemp height at 60 DAP in 2022. However, there was no significant difference in the plant height of hemp among soil-residual herbicides and nontreated control at harvest in both years. Some herbicides had a toxic effect on plants in the early stage, affecting plant height. However, plants recovered later from the herbicide toxicity, and no difference in plant height was observed at harvest. Although the information related to the effect of soil-residual herbicides on plant height of hemp grown under semi-arid conditions is minimal, comparable results have been reported in other preemergence herbicide studies in hemp. Anderson (2018) applied pendimethalin as a preemergence herbicide with $1.12 \text{ kg ai ha}^{-1}$ and reported no effect on hemp plant height at harvest. Pendimethalin application negatively affected the plant height during early growth stages, but the hemp overcame these effects in the later growth stages.

Similarly, pendimethalin resulted in 10% to 20% injury to hemp plants (cv. 'Finola') without affecting the plant height and seed yield (Maxwell 2016). In another field study, Flessner et al. (2020) found that using flumioxazin, sulfentrazone, linuron, acetochlor, diuron, pendimethalin, fomesafen, and dimethenamid-P as preemergence herbicides did not reduce the hemp (cv. 'Felina 32') plant height compared to the nontreated control. However, in the same experiment, preemergence herbicides pyroxasulfone, metribuzin, chlorimuron, norflurazon, S-metolachlor, and clomazone reduced hemp plant height by 45% to 82% compared to the nontreated control (Flessner et al. 2020). The difference or similarity in herbicide effect on plants depends upon their mode of action belonging to different groups. Pendimethalin and ethalfluralin belong to the same group, whereas acetochlor,

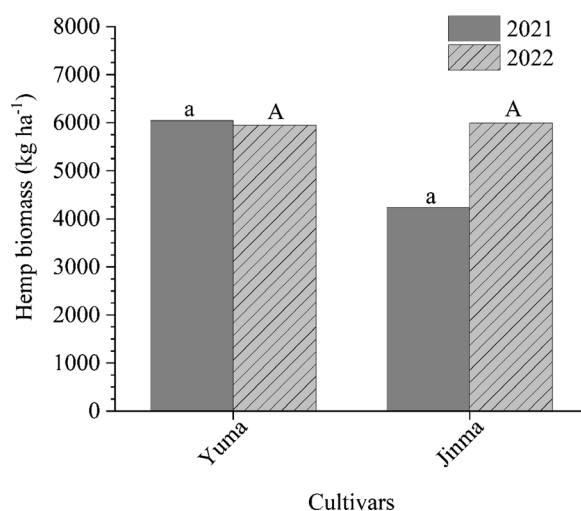


Figure 3. Effect of soil-residual herbicides on hemp cultivars in 2021 and 2022 at the experimental site in Lubbock, TX. Bars with different lowercase and uppercase letters indicate a significant difference among treatments in 2021 and 2022, respectively ($P \leq 0.05$, LSD test).

dimethenamid, pyroxasulfone, and metolachlor belong to another group. The herbicides sulfentrazone and fomesafen used in our experiment belong to the same group as flumioxazin. Metribuzin and chlorimuron are another group of herbicides with similar modes of action. The average plant height of 'Yuma' and 'Jinma' was statistically similar after all soil-residual herbicide treatments. However, the 'Yuma' plants were taller than the 'Jinma' throughout the growing season during both years.

Hemp biomass for both years is presented in Figure 2. In 2021, mesotrione significantly reduced hemp biomass compared to all other herbicidal treatments and produced 19.0% less hemp biomass than the nontreated control. Hemp biomass was 40.3% greater after ethalfluralin treatment than in the nontreated control. Sulfentrazone plus S-metolachlor, S-metolachlor, prometryn, and fomesafen produced 26.2%, 20.0%, 14.3%, and 7.6%, respectively, greater hemp biomass than the nontreated control; yet no significant difference was observed among these treatments. In year 2022, hemp treated with ethalfluralin, S-metolachlor, sulfentrazone plus S-metolachlor, fomesafen, and prometryn showed 12.1%, 12.6%, 14.8%, 42.3%, and 36.1%, respectively, higher biomass yield than the control; however, no significant difference was observed among these treatments. Minimal phytotoxicity in these treatments likely resulted in greater hemp biomass. In previous studies, Maxwell (2016) found that applying preemergence herbicides, including fomesafen and flazasulfuron, resulted in less phototoxicity and greater hemp biomass than mesotrione plus trifloxysulfuron. In a greenhouse experiment, Flessner et al. (2020) reported that metribuzin, clomazone, fomesafen, norflurazon, and pyroxasulfone reduced plant height and stand count and resulted in 70% to 95% hemp biomass reduction compared to nontreated control. Other preemergence herbicides, including pendimethalin, flumioxazin, and sulfentrazone, resulted in 30% to 60% hemp biomass reduction compared to the nontreated control (Flessner et al. 2020).

Different hemp cultivars, 'Yuma' and 'Jinma', showed no significant differences in hemp biomass yield (Figure 3). However, 'Yuma' displayed greater biomass yields than 'Jinma' in 2021 and 2022. Our results are somewhat in line with previous

Table 5. Effect of soil-residual herbicides on hemp weed count in 2021 and 2022 at the experimental site in Lubbock, TX

Treatments	Weed density			
	2021		2022	
	30 DAP	60 DAP	30 DAP	60 DAP
Cultivars (C)	Plants m ⁻²			
'Yuma'	27.5 a ²	10.7 a	20.7 a	16.3 a
'Jinma'	29.6 a	14.4 a	19.7 a	16.6 a
Herbicide (H)				
Ethalfuralin	34.7 bc	14.5 c	20.4 b	24.4 b
Bicyclopyrone plus S-metolachlor	6.3 d	0 d	–	–
Metribuzin plus S-metolachlor	5.2 d	0 d	–	–
Sulfentrazone plus S-metolachlor	4.3 d	6.5 cd	9.6 c	10.8 bc
Fomesafen	15.3 c	7.5 cd	15.2 bc	14.4 c
Mesotrione	28.3 bc	9.1 cd	–	–
Prometryn	49.3 b	26.5 b	15.1 bc	20.7 bc
S-metolachlor	23.0 cd	10.0 cd	11.8 c	11.8 bc
Control	86.6 a	39.3 a	49.2 a	43.1 a
C × H	NS ³	NS	NS	NS

²Mean values followed by different lowercase letters in each column indicate a significant difference in treatments ($P \leq 0.05$, Fisher's protected LSD test).

³Abbreviations: C × H, cultivar and herbicide interactions; NS, nonsignificant.

studies, where Ortmeier-Clarke *et al.* (2022) did not find any significant difference among cultivars while screening two hemp cultivars for tolerance to 44 different preemergence and postemergence herbicides under controlled conditions. Another preemergence herbicide, pendimethalin, has been used in several hemp cultivars and reported to be a safe preemergence herbicide (Flessner *et al.* 2020; Maxwell 2016, Ortmeier-Clarke *et al.* 2022), and it has been recommended for hemp weed control in China (Amaducci *et al.* 2015). Depending on the hemp cultivar, clopyralid, 2,4-D, and flumioxazin resulted in biomass reduction of 30% to 60%, 50% to 80%, and 70% to 85%, respectively, compared to untreated control (Ortmeier-Clarke *et al.* 2022).

Efficacy of Soil-Residual Herbicides on Weeds in Hemp

The nontreated control had the highest weed counts compared to other herbicide treatments at 30 DAP and 60 DAP in both years (Table 5). In 2021, bicyclopyrone plus S-metolachlor, metribuzin plus S-metolachlor, and sulfentrazone plus S-metolachlor had the lowest weed counts at 30 DAP, whereas bicyclopyrone plus S-metolachlor and metribuzin plus S-metolachlor recorded the lowest weed counts at 60 DAP. The weed counts were reduced by 60%, 93%, 94%, 95%, 82%, 67%, 43%, and 73% at 30 DAP and by 63%, 100%, 100%, 83%, 81%, 77%, 32%, 74% at 60 DAP with ethalfuralin, bicyclopyrone plus S-metolachlor, metribuzin plus S-metolachlor, sulfentrazone plus S-metolachlor, fomesafen, mesotrione, prometryn, and S-metolachlor, respectively, in the year 2021 as compared to the control. In 2022, the mixture of sulfentrazone plus S-metolachlor, and S-metolachlor alone had the lowest weed counts at 30 DAP, whereas fomesafen had the lowest weed counts at 60 DAP. The weed counts were reduced by 58%, 80%, 69%, 69%, and 76% at 30 DAP, and by 43%, 75%, 67%, 52%, and 73% at 60 DAP with ethalfuralin, sulfentrazone plus S-metolachlor, fomesafen, prometryn, and S-metolachlor, respectively, in the year 2022 as compared to nontreated control. However, the combination of bicyclopyrone plus S-metolachlor, as well as metribuzin plus S-metolachlor provided maximum weed control at 30 DAP. This combination also caused a total loss of hemp plants due to toxicity.

In previous studies, Byrd (2019) and Mettler (2021) also found a significant loss of hemp plants due to herbicide toxicity. Similarly, in the current study, mesotrione provided reasonable control of weeds (data not shown) but was very toxic to hemp plants and killed 70% of plants (Table 3). Mettler (2021) also revealed the toxic nature of mesotrione for hemp crop. This indicates that these three herbicides are toxic to hemp plants and unsafe for hemp production. In both years, the mixture of sulfentrazone plus S-metolachlor, S-metolachlor, ethalfuralin, and prometryn, significantly reduced weeds compared to the nontreated control at 30 DAP (Table 5). All these herbicides were also very safe on hemp plants and can be considered one of the safest soil-residual herbicides on hemp. These results align with the recommendation in China (Amaducci *et al.* 2015; Flessner *et al.* 2020). In both years, there was no significant difference in weed count between cultivars at both observation dates (30 DAP and 60 DAP).

Practical Implications

Weed management in industrial hemp faces significant challenges because of a lack of approved herbicides. Weed researchers throughout the United States are actively exploring herbicides that can be used in industrial hemp. Results indicate that some soil-residual herbicides worked very well with hemp, and few other herbicides showed toxicity on hemp plants and should not be used in industrial hemp. Bicyclopyrone plus S-metolachlor, metribuzin plus S-metolachlor, and mesotrione should be avoided in industrial hemp because of significant injury to hemp plants. However, soil-residual herbicides, ethalfuralin, sulfentrazone plus S-metolachlor, prometryn, and S-metolachlor appear suitable for hemp production and should be considered for further investigation.

Furthermore, these herbicides provided reasonable early weed control, and later, hemp canopy suppressed weeds, resulting in higher hemp biomass yield. Future research is needed to find the most promising preemergence and postemergence herbicides that can be used in hemp production under different climatic conditions. Also, the delta-9-tetrahydrocannabinol fiber and seed content following the herbicide application were not included in this study, which could be a viable area for future study that may bring another perspective to the safety of these herbicides in hemp.

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