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Short tile: Volunteer corn in sorghum

Control of glufosinate/glyphosate-resistant corn volunteers in imazamox- and quizalofop-resistant sorghum

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Abstract

Volunteer corn is a problem weed in sorghum fields rotated with corn. The commercial availability of imazamox-resistant (iGrowth™) and quizalofop-resistant (Doube Team™) sorghum allows the use of imazamox and quizalofop, respectively, for controlling grass weeds; however, information is not available for their efficacy for control of volunteer corn. The objectives of this study were to evaluate the efficacy of imazamox and quizalofop for control density, and biomass reduction of glufosinate/glyphosate-resistant corn volunteers in imazamox- and quizalofop-resistant sorghum. Two separate field experiments were conducted near Clay Center, NE, in 2023 and 2024. Imazamox (53 and 79 g ai ha^{-1}) applied early-postemergence (E-POST) and late-postemergence (L-POST) controlled 96% to 98% and 78% to 89% of corn volunteers 28 d after application (DAA) in 2023 and 2024, respectively in iGrowth sorghum. Similarly, quizalofop applied E-POST and L-POST (58 and 73 g ai ha^{-1}) provided 98% and 99% control of volunteer corn in 2023 and 2024, respectively in Double Team sorghum. Quizalofop reduced volunteer corn density (0 to 0.2 plants m^{-1}) and biomass (0 to 13 g m^{-2}) compared to nontreated control in both years. The results suggest that imazamox and quizalofop could be used as POST herbicides for control of glufosinate/glyphosate-resistant corn volunteers in imazamox- and quizalofop-resistant sorghum, respectively.

Nomenclature: Imazamox; quizalofop; corn, *Zea mays* L.; sorghum, *Sorghum bicolor* (L.) Moench ssp. *bicolor.*

Keywords: ALS-inhibitor; ACCase-inhibitor; chemical control; Double Team; herbicide-resistance; iGrowth; volunteer corn.

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Introduction

Nebraska is one of the largest corn-producing states in the United States, ranking third nationally in 2023 (NDA 2023). Corn production totaled approximately 44 billion kg from 4 million ha, contributing $8.6 billion to Nebraska's economy in 2023 (USDA-NASS 2023). Nebraska is also a leading sorghum-producing state, with about 137,593 ha under cultivation in 2023 (USDA-NASS 2023). Of this, 91,054 ha were harvested for grain, yielding 417 million kg and contributing $75.9 million to the state's economy (USDA-NASS 2023). Sorghum is a drought-tolerant crop, often favored for planting when drought conditions are anticipated (Assefa et al. 2010). In Nebraska, sorghum planting has increased following major drought events over the past thirteen years (Figure 1). For example, planted sorghum area more than doubled from 48,562 ha in 2012 to 101,172 ha after the 2012 drought. Similarly, acreage increased by 64%, from 78,914 ha in 2020 to 129,500 ha in 2021, following the 2020 drought. In 2023, grower interest in sorghum remained strong in Nebraska, with a 6% increase in planted area, reaching 137,593 ha (USDA-NASS 2023).

Some sorghum fields may follow corn, although corn-soybean and corn-corn are the major cropping rotations in Nebraska. In such cases, volunteer corn could become a significant problem weed in fields rotated to sorghum (Figure 2) (Alms et al. 2016; Krupke et al. 2009). Volunteer corn grows from seeds lost or shattered during the harvest operation or adverse weather event (Chahal et al. 2016). It is usually a problematic weed in corn-based rotations in the Midwestern United States (Jhala et al. 2021). It can be particularly challenging to manage if sorghum is grown in rotation after corn because 1) grass weeds are often challenging to control in sorghum due to limited availability of selective POST grass herbicides, and 2) sorghum is not genetically engineered for glyphosate or glufosinate-resistance, thus preventing the use of these herbicides.

Only a few herbicides, such as atrazine and quinclorac, are registered for selective postemergence (POST) control of grass weeds in sorghum. No POST herbicide is available for selective control of volunteer corn in sorghum. Imazamox-resistant (iGrowth™; UPL, King of Prussia, PA, and Alta seeds, College Station, TX) sorghum was commercially released in 2021, which enabled the preemergence (PRE) and POST use of imazamox (ImiFlex, UPL, King of Prussia, PA) to control grass weeds. Similarly, quizalofop-resistant (Double Team™; S&W Seeds, Longmont CO, and Adama, Raleigh, NC) sorghum was introduced in 2021, which

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provided quizalofop (FirstAct, Adama, Raleigh, NC) as a selective POST herbicide option for managing grass weeds.

Herbicide-resistant sorghum cultivars offered an option to seed corn producers who are looking for an alternative crop for soybean that can control corn volunteers, especially during drought years. These producers can now rotate corn to iGrowth or Double Team sorghum and use imazamox (Group 2; Acetolactate synthase inhibitor) or quizalofop (Group 1; Acetyl CoA carboxylase-inhibitor), respectively, for controlling grass weeds; however, growers are looking for recommendations for control of volunteer corn in iGrowth and Double Team sorghum. The objectives of this study were to evaluate the efficacy of imazamox and quizalofop for control of glufosinate/glyphosate-resistant corn volunteers in imazamox (iGrowth)- and quizalofop (Double Team)-resistant sorghum, respectively, as well as their effect on volunteer corn density, biomass, and sorghum yield.

Materials and Methods

Experimental Site and Design

The field experiments were conducted in 2023 and 2024 at University of Nebraska–Lincoln's South Central Ag Lab near Clay Center, NE (40.58°N, 98.14°W). The soil had a pH of 6.8 and organic matter of 3.6% with silty clay loam texture (0.15:0.57:0.27; sand:silt:clay). Two separate field experiments were conducted, one for imazamox (iGrowth)-resistant sorghum and another for quizalofop (Double Team)-resistant sorghum. The field experiments were designed as randomized complete blocks with three replications. An individual plot size was 3 m wide and 9 m long that included four sorghum rows spaced 76 cm. The imazamox-resistant sorghum experiment consisted of six herbicide treatments: imazamox at 53 and 79 g ai ha^{-1} applied PRE, early-POST (E-POST), and late-POST (L-POST). Ammonium sulfate (AMS) at 2.5% v/v and non-ionic surfactant (NIS) at 0.25% v/v was mixed with imazamox for the E-POST and L-POST applications. The quizalofop-resistant sorghum experiment consisted of six treatments: quizalofop at 58 and 73 g ai ha^{-1} applied E-POST, L-POST, and E-POST followed by (fb) L-POST. Quizalofop was mixed with NIS at 0.25% v/v. Nontreated and weed-free controls were included in both experiments for a comparison.

Agronomic Practices and Herbicide Applications

To simulate volunteer corn, the bin-run glufosinate/glyphosate-resistant corn was cross-planted 4.5 cm deep in 76 cm rows at 55,000 seeds ha^{-1} on April 27, 2023, and May 15, 2024. The imazamox-resistant (Advanta G2168IG) and quizalofop-resistant (SP 58M85) sorghum were planted at 285,000 seeds ha^{-1} on May 5, 2023, and May 15, 2024. To control other weeds, both experimental sites received pre-plant application of atrazine/mesotrione/*S*-metolachlor (Lumax EZ; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,286 g ai ha^{-1} in 2023 and atrazine/mesotrione/*S*-metolachlor at 2,779 g ai ha^{-1} plus glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,541 g ae ha^{-1} along with 3% v/v AMS and 1% v/v crop oil concentrate (COC) in 2024. For control of Palmer amaranth (*Amaranthus palmeri* S. Watson), the experimental sites received separate POST application of dicamba (Clarity; BASF Corporation, Research Triangle Park, NC) at 280 g ae ha^{-1} plus acetochlor (Warrant; Bayer Crop Science, St. Louis, MO) at 1,681 g ai ha^{-1} on June 5, 2023 and dicamba at 280 g ae ha^{-1} plus atrazine (Atrazine 4L, Winfield Solutions, LLC, St. Paul, MN) at 1,400 g ai ha^{-1} on June 7, 2024. Weed-free treatment in the imazamox-resistant sorghum experiment received a POST application of imazamox at 53 g ai ha^{-1} plus dicamba at 280 g ae ha^{-1} plus NIS 0.25 % v/v. For the quizalofop-resistant sorghum experiment, weed-free treatment received quizalofop at 58 g ai ha^{-1} plus bromoxynil/pyroxasulfone (Huskie; Bayer Crop Science, St. Louis, MO) at 216 g ai ha^{-1} along with NIS 0.25% v/v.

In the imazamox-resistant sorghum experiment, E-POST herbicides were applied on May 30, 2023 (10 cm sorghum and V4 volunteer corn), and June 7, 2024 (15 cm sorghum and V3 volunteer corn). Late-POST herbicides were applied on June 12, 2023 (46 cm sorghum and V7 volunteer corn), and June 19, 2024 (51 cm sorghum and V6 volunteer corn). In the quizalofop-resistant sorghum experiment, quizalofop was applied E-POST on June 5, 2023 (15 cm sorghum and V5 volunteer corn), and June 10, 2024 (15 cm sorghum and V4 volunteer corn). Quizalofop was applied L-POST on June 12, 2023 (46 cm sorghum and V7 volunteer corn), and June 19, 2024 (46 cm sorghum and V6 volunteer corn). In 2023, the average temperature and relative humidity during the week following E-POST herbicide applications were approximately 22 C and 68 to 69%, respectively; for L-POST herbicide applications, they were around 19 C and 65% (Figure 3). In 2024, the week following E-POST applications had average temperatures around 23 to 24 C with relative humidity of 64 to 65%, while for L-POST herbicide applications, the temperature was around 25 C with 71% humidity. Herbicides were applied using a CO_2-pressurized backpack sprayer with five TeeJet AIXR 11002 nozzles (Spraying Systems Co., Wheaton, IL). The sprayer delivered 140 L ha^{-1} of spray volume at 276 kPa.

Data Collection and Statistical Analysis

Volunteer corn control was visibly assessed on a scale of 0% (no control) to 100% (complete control) 14, 28, 42, and 56 d after application (DAA). The sorghum injury was assessed on a similar scale of 0% (no injury) to 100% (completely dead plant) 14 DAA. Volunteer corn density was recorded at 28 DAA by counting the number of volunteer corn plants in a one-meter row (n = 3). Volunteer corn biomass was determined by cutting the plants from 0.25 m^2 quadrat in each plot, and drying the biomass to constant weight in an oven at 70 C. In 2024, imazamox-resistant sorghum was harvested from the central two rows in each plot using a plot combine, and then grain yield was adjusted to 14% moisture content.

Data were analyzed using R software (version 4.2.2; R Core Team, 2024). Treatment and year interaction was evaluated, and data were combined if year and treatment × year interactions were non-significant. The nontreated (0% control) and weed-free (100% control) treatments lacked variance; therefore, they were removed from the analysis for volunteer corn control data. In the ANOVA model, treatment was considered a fixed factor and replication was treated as a random factor. The normality assumption of ANOVA was checked using *shapiro.test*. If the data were normal, it was modeled using the LME4 package (Bates et al. 2023). If the data did not fulfil normality assumption, it was modeled using the GLMMTMB package (Brooks et al. 2023) with beta distribution (link = “logit”) for percent volunteer corn control data and negative binomial distribution (link = “log”) for volunteer corn density data (Stroup 2015). Tukey’s ad-hoc test was conducted using the EMMEANS package to separate treatment means (Lenth et al. 2022).

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Results and Discussion

Volunteer corn control

Volunteer corn control differed between years (2023 and 2024) in both experiments (Tables 1 and 2). In imazamox-resistant sorghum experiment, imazamox at 79 g ai ha^{-1} applied PRE provided 38% control of volunteer corn 28 DAA in 2024 (Table 1). Control of volunteer corn was relatively lower in 2023, likely because volunteer corn had already begun germinating at the time of imazamox applied PRE. Currie and Geier (2022) reported 63% volunteer corn control 28 DAA with imazamox applied PRE at 79 g ai ha^{-1} in Kansas. E-POST applications of imazamox provided ≥96% control of volunteer corn 28 DAA in 2023 (Figure 4), though reduced efficacy was observed in 2024. Atrazine plus dicamba was applied for Palmer amaranth control on the day of E-POST application in 2024, which may have impacted imazamox efficacy. Schuster et al. (2007) reported reduced absorption and translocation of group 2 herbicides when mixed with atrazine and mesotrione. Additionally, although imazamox is recommended to be applied at least one hour before rainfall (Anonymous 2020), 1.4 cm of rainfall occurred on the night of the E-POST application in 2024 (Figure 3), which may have further affected efficacy. Currie and Geier (2022) found that imazamox (53 g ai ha^{-1}) applied to 25-30 cm volunteer corn achieved 99% control 42 DAA in imazamox-resistant sorghum in Kansas. Imazamox applied L-POST provided ≥73% control 28 DAA.

By 56 DAA, L-POST applications demonstrated increased volunteer corn control, achieving 88% to 94% control in 2023 and 97% to 98% control in 2024. Currie et al. (2023) reported 93% volunteer corn control 52 DAA using imazamox (53 g ai ha^{-1}) mixed with atrazine (1,120 g ai ha^{-1}) applied to volunteer corn at the 8-15 cm and imazamox-resistant grain sorghum at the 4-5 leaf stage in Kansas. A higher imazamox rate (79 g ai ha^{-1}) did not result in substantially greater control compared to the lower rate (53 g ai ha^{-1}) across PRE, E-POST, and L-POST applications. In 2023, L-POST applications exhibited 19% to 23% lower volunteer corn control 14 DAA (53% versus 72% to 76%), and 23% to 25% lower control 28 DAA (73% versus 96% to 98% control) compared to E-POST applications. This difference likely reflects the smaller growth stage (V3) of volunteer corn at the time of E-POST compared to the later stage (V6) during L-POST applications.

Quizalofop, applied E-POST or L-POST usually provided ≥93% control of volunteer corn by 28 DAA across both years, except for the lower rate applied E-POST in 2024 (Table 2;

Figure 5). This might be due to potential antagonism from dicamba applied three days before quizalofop for Palmer amaranth control. It has been reported that applying a broadleaf herbicide, such as dicamba, three days before quizalofop is not sufficient to alleviate graminicide antagonism (Culpepper et al. 1998). A seven-day interval after a POST broadleaf herbicide is recommended for sequential applications (Anonymous 2021).

Quizalofop is an effective herbicide for controlling volunteer corn and usually a single application is sufficient. For example, Striegel et al. (2020) reported 99% control of V5 and V7 glufosinate/glyphosate-resistant volunteer corn with quizalofop (31 and 39 g ai ha^{-1}) 28 DAA in Nebraska. Similarly, Singh et al. (2023) reported 99% control of V3 and V6 glufosinate/glyphosate-resistant volunteer corn with quizalofop at 46 and 93 g ai ha^{-1}. There was no difference in quizalofop efficacy of the two rates at any time point among L-POST and E-POST fb L-POST applications. On average, 2% to 5% sorghum injury was observed with quizalofop 14 DAA in E-POST fb L-POST program (data not shown).

Volunteer corn density and biomass

Volunteer corn density in imazamox-resistant sorghum study ranged between 3.8 to 4.0 plants m^{-1} when no herbicide was applied (Table 3). Imazamox applied E-POST decreased volunteer corn density to 0.2 to 0.3 plants m^{-1} in 2023. The volunteer corn biomass for non-treated control was 187 g m^{-2} and 227 g m^{-2} in 2023 and 2024, respectively. Imazamox applied POST reduced volunteer corn biomass to 0-47 g m^{-2} and 71-104 g m^{-2} in 2023 and 2024, respectively.

The nontreated control in quizalofop-resistant sorghum experiment has volunteer corn density and biomass of 3.3 to 4.1 plants m^{-1} and 255 to 412 g m^{-2}, respectively (Table 4). Quizalofop reduced volunteer corn density and biomass compared to the nontreated control in both years. Soltani et al. (2015) reported 62% to 74% and 75% to 82% reduction in volunteer corn density and biomass 42 DAA, respectively, with quizalofop (36 and 72 g ai ha^{-1}) applied POST. Striegal et al. (2020) noticed a 66% reduction in glufosinate/glyphosate-resistant volunteer corn biomass with quizalofop at 31 g ai ha^{-1}.

Sorghum yield

Imazamox-resistant sorghum yield correlated with the level of volunteer corn control. The nontreated control (3,111 kg ha^{-1}) had 56% yield loss compared to weed-free control (7,127 kg ha^{-1}; Table 3). This yield loss may have occurred as volunteer corn is reported to be significantly competitive with sorghum (Singh et al. 2024). Studies on sorghum yield loss due to volunteer corn interference appear scarce, although recent research addresses its control in sorghum (Currie and Geier 2022; Currie et al. 2023). Imazamox applied L-POST had a similar yield (7,424 to 7,773 kg ha^{-1}) as weed-free control. Imazamox applied PRE at 79 g ai ha^{-1} (5,479 g ai ha^{-1}) had 1,668 kg ha^{-1} less yield than weed-free control (7,127 kg ha^{-1}).

Practical Implications

Results suggest that recently developed herbicide-resistant sorghum technologies provide growers with flexibility to rotate from corn to sorghum while managing glufosinate/glyphosate-resistant volunteer corn through POST applications of imazamox and quizalofop in imazamox- and quizalofop-resistant sorghum, respectively. Some variability in efficacy was observed when applications were made close to broadleaf herbicide applications. Additionally, volunteer corn from Enlist hybrids, which are resistant to aryloxyphenoxypropionates, could pose a challenge. If quizalofop-resistant sorghum is planted following Enlist corn, quizalofop will not control Enlist volunteer corn; however, imazamox will remain effective in imazomox-resistant sorghum. Therefore, selection of herbicide-resistant sorghum should be made carefully, based on the herbicide-resistant traits of corn planted in the prevision year. In addition, herbicide-resistant sorghum should not be grown in consecutive years (Anonymous 2020, 2021). For example, imazamox-resistant sorghum requires an 18-month interval following imazamox application before it can be planted again in the same field (Anonymous 2020). Further, there is an 8.5-month planting interval for corn (non-Clearfield field corn, seed corn, sweet corn, and popcorn) after imazamox application (Anonymous 2020). Soybean has no planting interval after imazamox application; thus, soybean can be planted in rotation with imazamox-resistant (iGrowth) sorghum.

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Competing Interests

The authors declare that they have no competing interests.

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Table 1. Volunteer corn control with imazamox in imazamox-resistant (iGrowth) sorghum 14, 28, 42 and 56 d after application (DAA) in field experiments conducted in 2023 and 2024 near Clay Center, NE[a].

Treatment	Rate[c]	Application time[c]	Volunteer corn control[d]															
	g ai ha^{-1}		14 DAA				28 DAA				42 DAA				56 DAA			
			2023		2024		2023		2024		2023		2024		2023		2024	
			---%---															
Nontreated control	-	-	0		0		0		0		0		0		0		0	
Weed-free[b]	-	-	100		100		100		100		100		100		100		100	
Imazamox	53	PRE	13	c	11	d	10	c	18	b	8	b	8	d	7	d	6	d
Imazamox	79	PRE	12	c	15	cd	10	c	38	b	10	b	17	cd	5	d	17	c
Imazamox	53	E-POST	72	a	37	cd	96	a	40	b	97	a	33	bc	98	a	42	b
Imazamox	79	E-POST	76	a	39	bc	98	a	42	b	98	a	42	bc	97	ab	38	b
Imazamox	53	L-POST	53	b	67	ab	73	b	78	c	84	a	91	a	94	b	97	a
Imazamox	79	L-POST	53	b	68	a	73	b	89	c	79	a	99	a	88	c	98	a
P-value			<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	

[a] The experimental site received pre-plant application of atrazine/mesotrione/*S*-metolachlor (Lumax EZ; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,286 g ai ha^{-1} in 2023 and atrazine/mesotrione/*S*-metolachlor at 2,779 g ai ha^{-1} plus glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,541 g ae ha^{-1} along with 3% v/v ammonium sulfate and 1% v/v crop oil concentrate in 2024 for early season weed control.

[b] The weed-free treatment received a postemergence application of imazamox at 53 g ai ha^{-1} plus dicamba at 280 g ae ha^{-1} along with 0.25 %v/v non-ionic surfactant.

[c] Abbreviations: ai, active ingredient; E-POST, early postemergence; L-POST, late postemergence, PRE; preemergence.

[d] Means presented within each column with no common letter (s) differ significantly as per Tukey’s test at $P \leq 0.05$.

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Table 2. Volunteer corn control with quizalofop in quizalofop-resistant (Double Team) sorghum 14, 28, 42, and 56 d after application (DAA) in field experiments conducted in 2023 and 2024 near Clay Center, NE[a].

Treatment	Rate[c]	Application time[c]	Volunteer corn control[d]															
	g ai ha^{-1}		14 DAA				28 DAA				42 DAA				56 DAA			
			2023		2024		2023		2024		2023		2024		2023		2024	
			---------------------% ---------------------															
Nontreated control	-	-	0		0		0		0		0		0		0		0	
Weed-free control[b]	-	-	100		100		100		100		100		100		100		100	
Quizalofop	58	E-POST	97	a	42	c	98	a	61	b	99	a	52	b	99	a	64	b
Quizalofop	73	E-POST	96	a	99	a	98	a	99	a	99	a	98	a	99	a	99	a
Quizalofop	58	L-POST	68	b	99	a	93	a	99	a	97	a	99	a	97	a	99	a
Quizalofop	73	L-POST	83	ab	99	a	96	a	99	a	97	a	99	a	97	a	99	a
Quizalofop fb quizalofop	58	E-POST fb L-POST	96	a	88	b	97	a	99	a	99	a	99	a	99	a	99	a
Quizalofop fb quizalofop	73	E-POST fb L-POST	97	a	95	ab	98	a	99	a	99	a	99	a	99	a	99	a
P-value			<0.001		<0.001		NS		<0.001		NS		<0.001		NS		<0.001	

[a] The entire experimental site received pre-plant application of atrazine/mesotrione/*S*-metolachlor (Lumax EZ; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,286 g ai ha^{-1} in 2023 and atrazine/mesotrione/*S*-metolachlor at 2,779 g ai ha^{-1} plus glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,541 g ae ha^{-1} along with 3% v/v ammonium sulfate and 1% v/v crop oil concentrate in 2024 for early season residual weed control.

[b] The weed-free control received a postemergence application of quizalofop at 58 g ai ha^{-1} plus bromoxynil/pyroxasulfone (Huskie; Bayer Crop Science, St. Louis, MO) at 216 g ai ha^{-1} along with 0.25% v/v non-ionic surfactant.

[c] Abbreviations: ai, active ingredient; E-POST, early postemergence; fb, followed by; L-POST, late postemergence, PRE; preemergence.

[d] Means presented within each column with no common letter (s) differ significantly as per Tukey's test at $P \leq 0.05$.

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Table 3. Effect of imazamox applied at different timings on volunteer corn density and biomass 28 d after application (DAA) and grain yield in imazamox-resistant (iGrowth) sorghum in field experiments including in 2023 and 2024 near Clay Center, NE[a].

Treatment	Rate[c]	Application time[c]	Volunteer corn density[d]				Volunteer corn biomass[d,e]				Imazamox-resistant sorghum yield	
	$g\ ai\ ha^{-1}$		28 DAA				28 DAA					
			2023		2024		2023		2024		2024	
			plants m^{-1}				$g\ m^{-2}$				$kg\ ha^{-1}$	
Nontreated	-	-	4	a	3.8	ab	187	a	227	a	3,111	d
Weed-free[b]	-	-	0	-	0	-	0	-	0	-	7,127	ab
Imazamox	53	PRE	3.3	ab	4	a	106	b	183	ab	4,046	cd
Imazamox	79	PRE	4	a	3.2	ab	111	b	137	ab	5,479	bc
Imazamox	53	E-POST	0.3	c	3.3	ab	6	c	93	ab	6,043	abc
Imazamox	79	E-POST	0.2	c	3.4	ab	0	c	94	ab	5,341	bcd
Imazamox	53	L-POST	2.3	b	2.3	bc	47	c	104	ab	7,424	ab
Imazamox	79	L-POST	2.7	ab	1.4	c	32	c	71	b	7,773	a
P-value			<0.001		<0.001		<0.001		<0.001		<0.001	

[a]The entire experimental site received pre-plant application of atrazine/mesotrione/*S*-metolachlor (Lumax EZ; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,286 g ai ha^{-1} in 2023 and atrazine/mesotrione/*S*-metolachlor at 2,779 g ai ha^{-1} plus glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,541 g ae ha^{-1} along with 3% v/v ammonium sulfate and 1% v/v crop oil concentrate in 2024 for early season residual weed control.

[b]The weed-free control received a postemergence application of imazamox at 53 g ai ha^{-1} plus dicamba at 280 g ae ha^{-1} along with 0.25 %v/v non-ionic surfactant.

[c]Abbreviations: ai, active ingredient; E-POST, early postemergence; L-POST, late postemergence, PRE; preemergence.

[d]Means presented within each column with no common letter(s) differ significantly as per Tukey's test at $P \leq 0.05$.

[e]The nontreated control included the biomass of volunteer corn and other weeds.

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Table 4. Effect of quizalofop applied early-postemergence and late-postemergence on volunteer corn density and biomass in quizalofop-resistant (Double Team) sorghum 28 d after application (DAA) in field experiments conducted in 2023 and 2024 near Clay Center, NE[a].

Treatment	Rate[c]	Application time[c]	Volunteer corn density[d]				Volunteer corn biomass[d]			
	g ai ha^{-1}		28 DAA				28 DAA			
			2023		2024		2023		2024	
			plants m^{-1}				g m^{-2}			
Nontreated control	-	-	3.3	a	4.1	a	255	a	412	a
Weed-free control[b]	-	-	0	-	0	-	0	-	0	-
Quizalofop	58	E-POST	0	b	1.9	b	0	c	104	b
Quizalofop	73	E-POST	0.2	b	0	c	13	b	0	c
Quizalofop	58	L-POST	0.8	b	0	c	57	b	0	c
Quizalofop	73	L-POST	0.3	b	0	c	28	b	0	c
Quizalofop fb quizalofop	58	E-POST fb L-POST	0.2	b	0	c	13	b	0	c
Quizalofop fb quizalofop	73	E-POST fb L-POST	0	b	0	c	0	c	0	c
P-value			<0.001		<0.001		<0.001		<0.001	

[a] The entire experimental site received pre-plant application of atrazine/mesotrione/*S*-metolachlor (Lumax EZ; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,286 g ai ha^{-1} in 2023 and atrazine/mesotrione/*S*-metolachlor at 2,779 g ai ha^{-1} plus glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,541 g ae ha^{-1} along with 3% v/v ammonium sulfate and 1% v/v crop oil concentrate in 2024 for early season residual weed control.

[b] The weed-free control received a postemergence application of quizalofop at 58 g ai ha^{-1} plus bromoxynil/pyroxasulfone (Huskie; Bayer Crop Science, St. Louis, MO) at 216 g ai ha^{-1} along with 0.25% v/v non-ionic surfactant.

[c] Abbreviations: ai, active ingredient; E-POST, early postemergence; fb, followed by; L-POST, late postemergence, PRE; preemergence.

[d] Means presented within each column with no common letter (s) differ significantly as per Tukey's test at $P \leq 0.05$.

[e]The nontreated control included the biomass of volunteer corn and other weeds.

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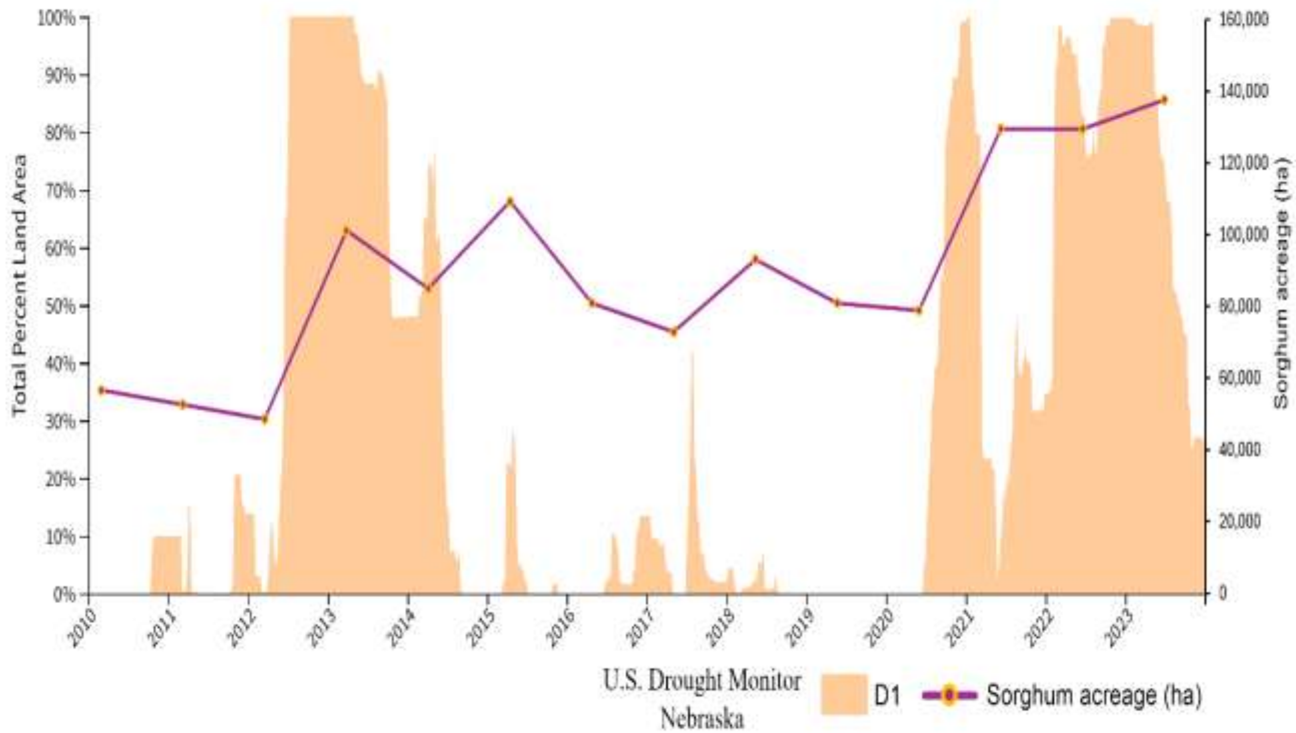

Figure 1. The total percentage of land area under moderate drought (D1) and sorghum planted area (ha) in Nebraska from 2010 to 2023. The historical drought graph was adapted from the U.S. Drought Monitor (2024). The D1 category is cumulative and includes severe, extreme, and exceptional drought areas. The data for sorghum planted acreage were obtained from USDA-NAS (2024).

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Figure 2. Volunteer corn in sorghum field in southcentral Nebraska (Photo by Amit Jhala).

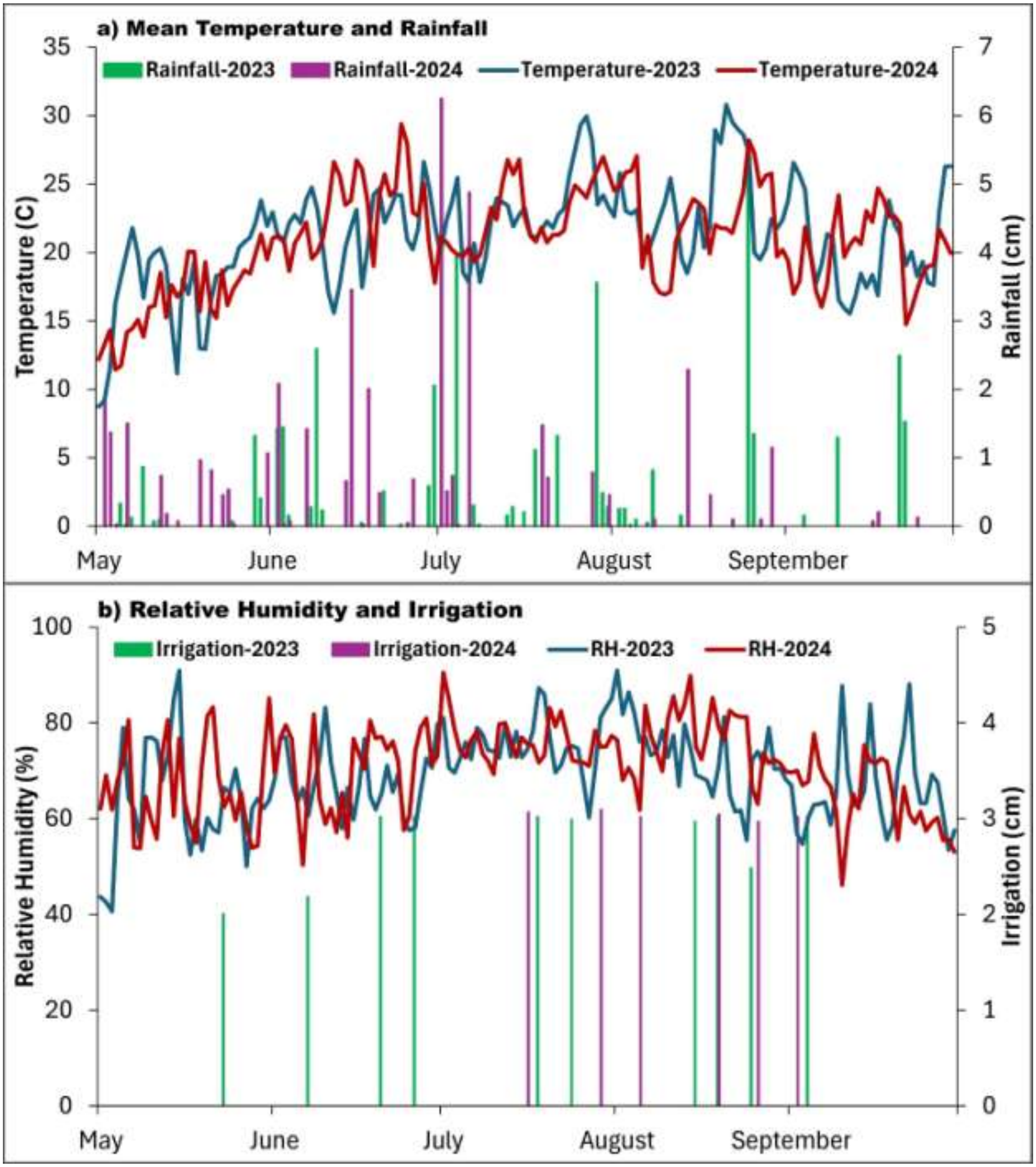

Figure 3. a) Mean air temperature and rainfall, and b) relative humidity and irrigation events during the 2023 and 2024 growing seasons at University of Nebraska−Lincoln's South Central Ag lab near Clay Center, NE.

Figure 4. Volunteer corn in a) nontreated, b) imazamox at 53 g ai ha^{-1} 31 days after early postemergence, and c) imazamox 53 g ai ha^{-1} 19 days after late postemergence application in imazamox-resistant (iGrowth) sorghum study conducted near Clay Center, NE in 2023 (Photos by Mandeep Singh).

Figure 5. Volunteer corn in a) nontreated, b) quizalofop at 58 g ai ha^{-1} 28 days after early postemergence application, and c) quizalofop at 58 g ai ha^{-1} 19 days after late postemergence application in quizalofop-resistant (Double Team) sorghum study conducted near Clay Center, NE in 2023 (Photos by Mandeep Singh).

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