Identifying herbicide-tolerant traits and developing herbicide strategies for weed control in pearl millet [*Pennisetum glaucum* (L.) R. Br.]

by

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Abstract

Weed management in pearl millet [*Pennisetum glaucum* (L.) R. Br.] presents a significant production challenge. The limited options for herbicides further complicate this issue. Additionally, the widespread evolution of herbicide resistance among weed species exacerbates the difficulty of management strategies. The main objectives of this thesis were to 1) identify and characterize the sensitivity of 56 pearl millet parental lines to POST-applied clethodim (136 g ai ha^{-1}), quizalofop-p-ethyl (QPE) (77 ai g ha^{-1}), imazamox (52 g ai ha^{-1}) and nicosulfuron (70 g ai ha^{-1}), and 2) investigate eight preemergence (PRE) herbicides (labeled in sorghum) for crop safety and weed control in three pearl millet hybrids, and 3) test various postemergence (POST) herbicides for crop safety and weed control in pearl millet hybrids. All tested parental lines were found sensitive to clethodim and QPE, with only four lines showing minimal survival (2% to 12%) but still suffering significant injury (90% to 95%) at 21 days after application (DAA). However, variable responses were observed to both imazamox and nicosulfuron. The survival rate with imazamox and nicosulfuron ranged from 70% to 100%, with visible injury and biomass reduction ranging from 5% and 70%. Three pearl millet parental lines with low sensitivity to imazamox (ARCH35R, 45R, and 73R), two lines with low sensitivity to nicosulfuron (ARCH45R and 73R), one line with high sensitivity (ARCH21B), and a susceptible sorghum (*Sorghum bicolor* L. Moench) hybrid (P84G62) to both herbicides were further characterized. Dose-response assays revealed that ARCH35R, 45R, and 49R were significantly less sensitive to imazamox, with reduced sensitivity of 7.7- to 12.2-fold compared to the highly sensitive ARCH21B and the sorghum hybrid. For nicosulfuron, ARCH45R and 49R showed 2.5- to 6.0-fold reduced sensitivity compared to ARCH21B and the sorghum hybrid. These findings

represent the first report of reduced sensitivity to imazamox and nicosulfuron in pearl millet lines, suggesting these lines could be useful for managing grass weeds in the field.

The second objective focused on evaluating eight preemergence (PRE) herbicides, including *S*-metolachlor, acetochlor, atrazine, and mesotrione, and their combinations for crop safety and weed control in three pearl millet hybrids in a field study over two growing seasons. Results showed that the application of *S*-metolachlor alone or in combination with atrazine, mesotrione, or both caused severe injury (>95%) to all three hybrids at 28 DAA. In contrast, mixtures of acetochlor with atrazine showed variable injury levels, ranging from 50% to 96% across three hybrids. However, atrazine or mesotrione applied alone or in combination caused minimal injury (<5%) to the hybrids, indicating good crop safety. Regarding weed control, all tested PRE herbicides provided excellent control of Palmer amaranth, with control levels reaching ≥90% at 28 DAA, except for *S*-metolachlor (86% control). The combination of mesotrione and acetochlor with atrazine was especially effective against green foxtail, achieving ≥ 99% control. These results suggest that the combination of atrazine, mesotrione, and their mixtures can be used safely for controlling Palmer amaranth and green foxtail in pearl millet without causing significant crop injury.

The third objective evaluated the safety and effectiveness of postemergence (POST) herbicides on five pearl millet hybrids in greenhouse and three hybrids in field study. In the greenhouse study, all POST herbicides caused only minimal injury (1% to 5%) at 28 DAA, except for imazamox and nicosulfuron, which caused moderate injury (22% to 27%). Similarly, field studies showed minimal injury (1% to 3%) from all the POST herbicides, except imazamox and nicosulfuron. POST herbicides, including 2,4-D, dicamba, bromoxynil + pyrasulfotole, and the combination of 2,4-D + bromoxynil + fluroxypyr provided 88% to 91% control of Palmer

amaranth and significantly reduced its density (2 to 4 plants m^{-2}). In contrast, imazamox and nicosulfuron were less effective in controlling Palmer amaranth, with only 60% to 65% control and a higher density of 8 plants m^{-2}. However, imazamox and nicosulfuron were effective against green foxtail, providing 91% to 92% control and reducing its density to 2 plants m^{-2} at 42 DAA. Among all tested hybrids, the Hyb1 outperformed the other hybrids at two field sites. The combination of 2,4-D + bromoxynil + fluroxypyr resulted in the highest grain yield for Hyb1 (3,866 to 4,619 kg ha^{-1}), Hyb2 (2,222 to 3,699 kg ha^{-1}), and Hyb3 (822 to 1,315 kg ha^{-1}).

Overall, results from this thesis provide valuable insights into the herbicide sensitivity of pearl millet and its potential use for weed control. Reduced sensitivity to imazamox and nicosulfuron in pearl millet lines may potentially be used in developing herbicide-tolerant cultivars. Additionally, PRE herbicide applications, particularly those involving atrazine and mesotrione, showed promise for controlling Palmer amaranth and green foxtail while maintaining crop safety. Majority of tested POST herbicides were found to be safe for pearl millet and effective in controlling Palmer amaranth. POST applied imazamox and nicosulfuron were found particularly effective against green foxtail. Overall, these results highlight the potential for using selective PRE and POST herbicide strategies tested in this research to improve weed management in pearl millet production.

Table of Contents

List of Figures viii
List of Tables ix
Acknowledgements xi
Chapter 1 - Literature Review 1
Chapter 2 - Sensitivity of Pearl Millet (*Pennisetum glaucum* [L.] R. Br.) Parental Lines to POST Herbicides: Clethodim, Quizalofop-P-ethyl, Imazamox, and Nicosulfuron 9
2.1. Abstract 9
2.2. Introduction 10
2.3. Materials and Methods 13
2.3.1. Plant Material 13
2.3.2. Single-Dose Bioassays 13
2.3.3 Dose-Response Bioassays 15
2.3.4. Statistical Analysis. 16
2.4. Results and Discussion 17
2.4.1 Single Dose Bioassays 17
2.4.2. Dose-Response Bioassays 19
2.5. Practical Implications 21
Chapter 3 - Pearl Millet [*Pennisetum glaucum* (L.) R. Br.] Hybrids Tolerance and Weed Control with Preemergence Herbicides 37
3.1. Abstract 37
3.2. Introduction 38
3.3. Material and Methods 40
3.3.1. Pearl Millet Hybrids 40
3.3.2. Field Experiment 40
3.3.4. Data Collection 41
3.3.5. Statistical Analyses 42
3.4. Results and Discussion 42
3.4.1. Percent Visual Injury 43
3.4.2. Weed Control, Density, and Biomass 44

3.4.2.1. Palmer amaranth control 44
3.4.2.2. Green foxtail control 45
3.4.3. Weed Density 45
3.4.3.1. Palmer amaranth density 45
3.4.3.2. Green foxtail density 46
3.4.4. Total weed biomass 47
3.4.5. Grain Yield 48
3.5. Practical Implications 48
Chapter 4 - Postemergence Herbicides for Crop Safety and Weed Control in Pearl Millet [*Pennisetum glaucum* (L.) R. Br.] Hybrids 56
4.1. Abstract 56
4.2. Introduction 57
4.3. Material and Methods 60
4.3.1. Greenhouse Experiment 60
4.3.2. Field Experiment 61
4.3.3. Data Collection 62
4.3.4. Statistical Analyses 62
4.4. Results and Discussion 63
4.4.1. Greenhouse Study 63
4.4.1.1. Percent visual injury 63
4.4.1.2. Shoot dry biomass reduction 64
4.4.2. Field Experiments 64
4.4.2.1. Pearl millet injury 64
4.4.2.2. Palmer amaranth control and density 65
4.4.2.3. Green foxtail control and density 67
4.4.2.4. Pearl millet grain yield 68
4.5. Practical Implications 70
Chapter 5 - Conclusion and Future Research 78
Chapter 6 - References 80

List of Figures

Figure 2.1. Shoot dry biomass reduction (% of nontreated) of pearl millet parental lines and commercial sorghum hybrid treated with different doses of imazamox at 21 days after application (DAA). 35

Figure 2.2. Shoot dry biomass reduction (% of nontreated) of selected pearl millet parental lines and conventional sorghum hybrid treated with various doses of nicosulfuron at 21 days after application (DAA). 36

List of Tables

Table 2.1. List of 56 advanced parental lines of pearl millet used for herbicide screening. 23
Table 2.2. List of selected POST herbicides used in this study. 24
Table 2.3. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of pearl millet parental lines treated with clethodim at 21 days after application (DAA). 25
Table 2.4. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of pearl millet parental lines treated with quizalofop at 21 days after application (DAA). 27
Table 2.5. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of pearl millet parental lines treated with imazamox at 21 days after application (DAA)..... 29
Table 2.6. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of Pearl millet parental lines treated with nicosulfuron 21 days after application (DAA)..... 31
Table 2.7. Regression estimates of the 3-parameter log-logistic equation fitted to shoot dry biomass reduction (% of nontreated) of selected pearl millet parental lines sprayed with different imazamox doses 21 days after application (DAA)..... 33
Table 2.8. Regression estimates of the 3-parameter log-logistic equation fitted to shoot dry biomass reduction (% of nontreated) of selected pearl millet lines sprayed with different nicosulfuron doses 21 days after application (DAA). 34
Table 3.1. List of selected preemergence herbicides, rates, adjuvants, and manufacturers tested on the pearl millet hybrids. 50
Table 3.2. Averaged monthly air temperature and total cumulative precipitation at Kansas State University Agricultural Research Center in Hays, KS, during the 2023 and 2024 growing seasons. 51
Table 3.3. Percent visual injury of pearl millet hybrids treated with various preemergence herbicides at 14, 28, and 56 days after application (DAA). 52
Table 3.4. Percent visual control of Palmer amaranth and green foxtail with preemergence herbicides at 14, 28, and 56 days after application (DAA) averaged across 3 pearl millet hybrids. 53
Table 3.5. Palmer amaranth and green foxtail density and total weed biomass with PRE emergence herbicides at 28 and 56 days after application (DAA) averaged across 3 pearl millet hybrids at Kansas State University Agricultural Research Center in Hays, KS..... 54

Table 3.6. Grain yield of pearl millet hybrids under various preemergence herbicides averaged across two growing seasons at Kansas State University Agricultural Research Center, Hays, KS. 55
Table 4.1. List of selected POST herbicides, their rates, and adjuvants tested on pearl millet hybrids at Kansas State University Agricultural Research Center, Hays, KS. 72
Table 4.2. Average monthly air temperature and total cumulative precipitation at Kansas State University Agricultural Research Center, Hays, KS, during the 2023 and 2024 growing seasons. 73
Table 4.3. Effect of POST herbicides on visual injury (%) and shoot biomass reduction (% of nontreated) averaged across five pearl millet hybrids at 28 d after application (DAA) in greenhouse experiments at Kansas State University, Agricultural Research Center, Hays, Kansas. 74
Table 4.4. Percent visual crop injury, Palmer amaranth and green foxtail control, and density with POST herbicides averaged across three pearl millet hybrids at experimental site 1 at Kansas State University, Agricultural Research Center, Hays, Kansas..... 75
Table 4.5. Percent visual crop injury at 14 and 28 DAA with POST herbicides averaged across three pearl millet hybrids at experimental site 2 at Kansas State University, Agricultural Research Center, Hays, Kansas. 76
Table 4.6. Grain yield of three pearl millet hybrids as influenced by POST herbicides at two experimental sites at Kansas State University, Agricultural Research Center, Hays, Kansas. 77

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Chapter 1 - Literature Review

Pearl millet [*Pennisetum Glaucum* (L.) R. Br.] first originated in tropical western Africa around 4000 years ago (Upadhyaya et al. 2017). From there, it spread to different continents, including Asia, Africa, North America, and Australia (Yadav et al. 2016). It is widely cultivated on >30 million ha in arid and semi-arid regions of Asia, Africa, and some parts of the United States (Perumal et al. 2024). Pearl millet is cultivated around 20 million ha in Africa and about 11 million ha in Asia (Deevi et al. 2024). Among all pearl millet-producing countries, India is the largest producer, with 8.5 million tons of production. Asia and Africa contribute 41% of the global millet production, of which 60% is cultivated in Africa and 35% in Asia (Satyavathi et al. 2024). In the USA, around 60,000 hectares are under pearl millet production for fodder (Myers 2002; All India Coordinated Research Project on Pearl Millet 2022). Pearl millet is a versatile cereal cultivated for food, feed, and forage (Arora et al. 2003). Ninety million people across the world depend on pearl millet as a staple food for consumption and feed for livestock (Govindaraj et al. 2024).

Pearl millet is a highly significant cereal crop, ranking as the sixth most important crop globally after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum bicolor* L. Moench) (Satyavathi et al. 2021). Pearl millet plays a crucial role in ensuring food, feed, and nutritional security for millions of people around the world, particularly in regions where other staple crops struggle to thrive (Sharma et al. 2024). Pearl millet is a drought-tolerant crop that has been recognized as an essential climate-resilient species capable of withstanding extreme conditions, such as high temperatures, limited rainfall, and poor soil fertility Walsh and Lundgren (2024). Its ability to adapt to such adverse

environmental conditions, alongside its high nutritional value, positions it as a key crop for global food security in the face of climate change (Joshi et al. 2025).

One of the most striking characteristics of pearl millet is its remarkable resilience to harsh environmental conditions, particularly in regions affected by drought and high temperatures (Satyavathi et al. 2024). Pearl millet is a C_4 crop with a Kranz anatomy that enables efficient carbon fixation and water use (Swarna et al. 2024). This efficient photosynthetic pathway allows it to thrive in environments where other cereal crops would fail (Swarna et al. 2024). In particular, pearl millet can endure extreme temperatures exceeding 42 °C during its reproductive phase without a significant decrease in grain yield or quality (Howarth et al. 1996; Daduwal et al. 2024). This heat tolerance is especially important in regions experiencing rising temperatures due to climate change, making pearl millet an ideal crop for dryland areas (Paroda et al. 2024).

Furthermore, pearl millet can tolerate low soil fertility, high salinity, and poor water-holding capacity, which makes it suitable for cultivation in marginal soils that are unsuitable for other cereal crops such as maize, sorghum, and wheat (Bollam et al. 2024). The crop has relatively low water requirements, typically needing only 200 to 400 mm of water during its growing season, which is considerably less than many other major cereals (Prasad et al. 2022). This characteristic of pearl millet makes it a viable crop for rain-fed and irrigated systems in arid and semi-arid regions, particularly as water scarcity becomes a growing concern worldwide (Tonapi et al. 2024). Its ability to withstand drought and produce grain under adverse conditions makes it an indispensable crop for regions that are already facing or are expected to face water shortages (Yadav et al. 2024).

Moreover, pearl millet's ability to thrive in hot and dry conditions extends beyond its tolerance to high temperatures (Sine et al. 2024). The crop's adaptability to salinity, high-pH

soils, and low fertility further enhances its potential as a sustainable crop in environments affected by soil degradation (Jukanti et al. 2016). As such, it can provide an important alternative to traditional crops in areas where soil quality has been degraded due to overuse or poor management practices (Sharma et al. 2014).

In addition to its climate resilience, pearl millet is a nutritionally rich crop, offering a wide range of health benefits. Pearl millet had higher protein (14.0%), fat (5.7%), fiber (2.0%), and ash (2.1%) content (Sade 2009) when compared to the major cultivated cereal crops such as wheat (Kavitha and Parimalavalli 2014), rice (Ahmed et al. 2014), sorghum (Awadelkareem et al. 2015). It is an excellent source of energy, carbohydrates, proteins, fats, and dietary fiber, which contribute to its potential in addressing malnutrition and food insecurity. Compared to other major cereals, pearl millet stands out for its high protein content, which makes it particularly valuable in diets where protein intake is limited, such as in many low-income, food-insecure regions (Satyavathi et al. 2021). Its high fiber content (1.2 g/100 g) also makes it an ideal food for improving digestive health and reducing the risk of chronic diseases such as heart disease and diabetes (Nibhoria et al. 2024). Furthermore, pearl millet is rich in essential minerals such as iron (11 mg/100 g) and zinc (3.1 mg/100 g), which are critical for combating micronutrient deficiencies in many developing countries (Govindaraj et al. 2023). These micronutrients play a vital role in immune function, cognitive development, and overall health, highlighting pearl millet's potential as a 'nutri-cereal' for improving global nutritional security (Rai et al. 2012; Satyavathi et al. 2021).

One of the significant advantages of pearl millet is its low glycemic index (55), making it an excellent choice for individuals with diabetes or those seeking to manage blood sugar levels (Nambiar et al. 2011). This characteristic, along with its high protein and fiber content, makes it

a healthy alternative to other high-glycemic index grains such as rice or white bread (Nibhoria et al. 2024). Additionally, its ability to contribute to the daily intake of essential vitamins, including riboflavin, niacin, and thiamine, makes it a valuable food source for improving overall health (Dayakar et al. 2017).

Beyond its potential for human nutrition, pearl millet is also an important crop for livestock feed. The forage varieties of pearl millet have been shown to contain high levels of crude protein (12-14%) and dietary fiber (2.8-17.6%), making them an excellent choice for animal husbandry (Daduwal et al. 2024; Harinarayana et al. 2005; McCartor et al. 1977;). Furthermore, varieties with reduced lignin content, such as brown midrib mutants, offer improved forage digestibility, which is a critical factor in maximizing livestock productivity (Bhattarai et al. 2019; Uppal et al. 2015). This dual-purpose nature of pearl millet(as both a food and forage crop) makes it a versatile and valuable resource for farmers in regions where both human and livestock nutrition are critical concerns (Nagaraja et al. 2024). It is an excellent forage crop and has great potential (Kaushal et al. 2024). Its fodder is high in protein, calcium, phosphorus, and other minerals while being low in undesirable components such as hydrocyanic acid and oxalic acid (Gupta and Bhatnagar 2006). As a fodder crop, it is leafy, nutritious and palatable. It can be fed to animals at any crop stage and is primarily present in two plant morphologies: dwarf bushy type (used for grazing) and tall type (used for green fodder, silage, and hay) (Hancock and Greg 2010). It provides crude protein and total digestible nutrients to cattle at 33% and 66% less cost, respectively, as compared to the concentrated feed (Ravi et al. 2023), making it a valuable feed source for dairy farmers.

The United Nations declared the year 2023 as the International Year of Millets (IYM 2023). This International Year was a timely reminder of this important crop. It provides a unique

opportunity to raise awareness of and to direct policy attention to the nutritional and health benefits of millet consumption, the suitability of millets for cultivation under adverse and changing climatic conditions and creating sustainable and innovative market opportunities for many countries around the world for millets to benefit farmers and consumers globally (FAO Director-General QU Dongyu). In the U.S., the Central Great Plains (CGP) offer optimal conditions for the cultivation of pearl millet. Given its low water requirements, pearl millet presents a sustainable alternative in regions where water resources are increasingly scarce, such as in the CGP, where the depletion of the Ogallala Aquifer is a growing concern (Maman et al. 2004). Its robust adaptability also makes it a viable summer annual in three-year crop rotation systems, particularly in regions like western Kansas in the Midwest (Liebman et al. 2001). Its integration into these cropping systems can enhance sustainability, improve soil health, and contribute to water-use efficiency, aligning with the demands of climate-resilient agriculture (Raj et al. 2024).

Despite its numerous advantages, pearl millet faces significant challenges in its cultivation, with weed management being one of the most critical issues (Kumar et al. 2024). Weeds compete with the crop for vital resources such as nutrients, water, sunlight, and space, leading to reduced yields and, in some cases, even crop failure (Mishra 2015). The early growth stages of pearl millet are particularly vulnerable to weed competition due to its relatively slow initial growth rate. This makes it a poor competitor against weeds, especially when competing with aggressive grass and broadleaf species (Geetha et al. 2024). Research has shown that the critical period for weed control in pearl millet spans from 28 to 42 days after planting (Chaudhary et al. 2018). During this period, weeds can significantly reduce pearl millet grain yields, with reported yield losses ranging from 16% to 94%, depending on the density and

duration of weed infestation (Balyan et al. 1993). Sharma and Jain (2003) reported up to 40% loss in grain yield due to weed competition in pearl millet. Similarly, Banga (2000) reported a 55% reduction in pearl millet grain yield due to weeds.

All types of weeds, including grasses, sedges, and broad-leaved infest the millet crops during their early phase of growth (Khairwal et al. 2007). In the U.S. CGP, Reddy et al. (2014) reported Canada thistle [*Cirsium arvense* (L.) Scop.], kochia [*Kochia scoparia* (L.) Schrad.], redroot pigweed (*Amaranthus retroflexus* L.), green foxtail [*Setaria viridis* (L.) Beauv.], and palmer amaranth (*Amaranthus palmeri* S. Watson) as the most common troublesome weeds interfering with millet crops. Kumar et al. (2024) reported weed species that affect pearl millet include both grass weeds, such as Bermuda grass (*Cynodon dactylon*) and barnyard grass (*Echinochloa crus-galli*), as well as broadleaf species, including Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus tuberculatus*). The presence of these weeds can also affect the quality of the grain, leading to issues such as reduced seed size and lower nutritional value (Gaba et al. 2017). As a result, effective weed management is crucial for maximizing the yield and quality of pearl millet production (Chaudhary et al. 2018).

However, the lack of effective herbicide options in pearl millet exacerbates the problem (Kumar et al. 2024). While herbicide use has revolutionized weed control in major cereal crops, pearl millet lacks herbicide-tolerant varieties/hybrids, making it difficult for farmers to manage weeds efficiently (Bajwa et al. 2015). Additionally, the limited selectivity of available herbicides for both annual grass weeds and pearl millet further complicates the development of effective chemical weed control strategies (Mishra 2015). Furthermore, the evolution of herbicide-resistant weed biotypes, which has become a widespread issue in many agricultural regions, further complicates weed management in pearl millet fields (Heap 2025). Consequently,

alternative weed management strategies, including the development of herbicide-tolerant pearl millet hybrids, are essential to ensure sustainable production (Kumar et al. 2025).

The development of herbicide-tolerant crops has transformed weed management in major crops (Brookes 2014), but no such advancements have been made for pearl millet. The integration of herbicide tolerance into pearl millet breeding programs could provide significant benefits for farmers, particularly in areas where weed resistance to conventional herbicides is a growing concern (Tugoo et al. 2025). Identifying pearl millet parental lines with reduced sensitivity to Acetyl-CoA carboxylase (ACCase) (Group 1) and acetolactate synthase (ALS) (Group 2)-inhibiting POST herbicides may help in developing elite herbicide-tolerant hybrids that can potentially offer grass weed control options. Therefore, the focus of the research was to evaluate the sensitivity of advanced pearl millet parental lines to ACCase-inhibiting herbicides (clethodim and quizalofop) and ALS-inhibiting herbicides (imazamox and nicosulfuron) and to characterize the sensitivity levels of selected lines to imazamox and nicosulfuron. This study hypothesized that pearl millet parental lines may exhibit natural variation in their tolerance to these herbicides, which could provide POST herbicide options for grass weed control. Additionally, the identification of tolerant pearl millet parental lines could be used in future breeding programs to develop herbicide-tolerant hybrids.

Pearl millet is very susceptible to competition from weeds early in the lifespan of the crop. Therefore, efficient weed control at the pre-and post-emergence stages is all important. The second and third objectives of this research were to evaluate the effectiveness of various preemergence (PRE) and postemergence (POST) herbicides(commonly labeled for use in sorghum) for crop safety and weed control in pearl millet hybrids. The results of this study could

provide effective PRE and POST herbicide options to pearl millet growers, improving the overall efficiency and sustainability of pearl millet production.

In this context, the major objectives of this thesis were to 1) evaluate the sensitivity of pearl millet parental lines to POST-applied clethodim (136 g ai ha^{-1}), quizalofop-p-ethyl (QPE) (77 ai g ha^{-1}), imazamox (52 g ai ha^{-1}) and nicosulfuron (70 g ai ha^{-1}), and 2) investigate eight preemergence (PRE) herbicides (labeled in sorghum) for crop safety and weed control in three pearl millet hybrids, and 3) test various postemergence (POST) herbicides for crop safety and weed control in pearl millet hybrids.

Chapter 2 - Sensitivity of Pearl Millet (*Pennisetum glaucum* [L.] R. Br.) Parental Lines to POST Herbicides: Clethodim, Quizalofop-P-ethyl, Imazamox, and Nicosulfuron

2.1. Abstract

Pearl millet is a climate-resilient grain and forage crop. Weeds pose a major constraint to its successful production. Limited herbicide options for grass weed control in pearl millet is a serious problem. The objectives of this study were to 1) evaluate the sensitivity of pearl millet parental lines to POST-applied clethodim (136 g ai ha^{-1}), quizalofop-p-ethyl (QPE) (77 ai g ha^{-1}), imazamox (52 g ai ha^{-1}) and nicosulfuron (70 g ai ha^{-1}), and 2) characterize the sensitivity of selected lines to imazamox and nicosulfuron. A total of 56 parental lines were tested. Three lines with low sensitivity to imazamox (ARCH35R, 45R, and 73R), two to nicosulfuron (ARCH45R and 73R), one line with high sensitivity (ARCH21B), and a susceptible sorghum (SOR) hybrid (P84G62) to both herbicides were characterized. All parental lines were sensitive to clethodim and QPE (only four lines showed 2 to 12% survival with 90 to 95% injury at 21 d after application [DAA]). However, all parental lines showed variable sensitivity to imazamox and nicosulfuron (70 to 100% survival with 5 to 70% visible injury and shoot dry biomass reduction at 21 DAA). Dose-response assays revealed that ARCH35R, 45R, and 49R had 7.7 to 12.2 and 3.2- to 12.2-fold reduced sensitivity to imazamox compared to the ARCH21B and SOR, respectively. Similarly, ARCH45R and 49R had 2.5 to 6.0 and 1.5 to 3.7-fold reduced sensitivity to nicosulfuron compared to ARCH21B and SOR, respectively. These findings confirm the first report of reduced sensitivity to imazamox and nicosulfuron among pearl millet lines, suggesting their potential use for in-season grass weed control.

Nomenclature: Clethodim; imazamox; nicosulfuron; quizalofop; pearl millet, Pennisetum glaucum (L.) R. Br.

Keywords: Herbicide Sensitivity; Parental Lines

2.2. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is the 6th most important cereal crop after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum bicolor* L. Moench) grown with a global production over 31.0 M ha^{-1} (Kumar et al. 2022). It belongs to the Poaceae family and is grown globally for food, feed, and nutritional security (Mishra 2015). In comparison to other major cereals, it has high nutritional values and is a good source of fat (3 to 8%), proteins (8 to 19%), ash (1.6 to 2.4%), dietary fibers (1.2 g/100 g), and antioxidants (Uppal et al. 2015). In addition, pearl millet is a rich source of minerals (2.3 mg/100 g) particularly iron (11mg/100 g), zinc (3.1 mg/100 g), and other micro-nutrients like potassium, phosphorus, and vitamins such as riboflavin, niacin, and thiamine (Uppal et al. 2015). Forage pearl millet contains 2.8 to 17.6% fiber and 12 to 14% crude protein which is higher than corn silage (Banks and Stewart, 1998) with relatively low lignin concentration (Harinarayana et al. 2005). The development of brown mid-rib mutants with reduced lignin biosynthesis presents a great potential for improving the quality of forage pearl millet (Cherney et al. 1988; Degenhart et al. 1995; Gupta and Govintharaj 2023). Unlike sorghum, pearl millet is genetically free from prussic acid and tannins and hence suitable for grazing for livestock, dairy cows, and horses at any growing stage (Newman et al. 2010).

Pearl millet is grown in arid and semi-arid regions of Asia and Africa (Srivastava et al. 2020). In the United States of America (USA), pearl millet is mainly grown for grazing, hay,

cover crops, and forage with approximately 0.61 M ha^{-1} in production (Myers 2002). It is recognized as a potential forage and feed crop that is well-suited for double cropping in the United States (Wilson et al. 1996). It is well adapted to low soil fertility, high pH, low soil moisture, high temperature, high salinity, and limited rainfall areas where other cereals like maize, rice, sorghum, and wheat would fail (Sollenberger et al. 2020). It has a C_4 photosynthetic pathway and can withstand high temperatures and stress up to 42 °C during its reproductive phase (Howarth et al. 1996). Due to its ability to produce grain and forage in dry and hot climates and on soils nouitable for sorghum and corn, it is a good option for low input agricultural production systems (Jukanti et al. 2016).

Weed management is one of the most significant challenges in pearl millet production (Kumar et al. 2023a). Weeds compete with crops for nutrients, soil, moisture, sunlight, and space resulting in yield losses, low-quality grains, and decreased crop production (Diatta et al. 2016). Due to its early slow growth, pearl millet is a relatively poor competitor with weeds that can result in substantial grain yield losses (Cook et al. 2005). The critical period of weed control (CPWC) in pearl millet has been reported ranging from 28 to 42 days after planting (Chaudhary et al. 2018). Weed competition from both grass and broadleaf species at various densities has been reported to reduce pearl millet grain yield ranging from 16 to 94% (Balyan et al. 1993; Das and Yaduraju 1995; Sharma and Jain 2003). The extent of grain yield loss generally depends on the pearl millet cultivar/hybrid, nature, and intensity of weeds, duration of weed infestation, environmental factors, and management practices (Mishra 2015). Limited herbicide options with a potentially narrow selectivity range between annual grass weeds and pearl millet are major constraints in developing a robust chemical-based weed control program (Dowler and Wright

1995; Mishra 2015). The evolution of herbicide-resistant weed biotypes across various regions further exacerbates the problem of weed control in pearl millet (Heap 2024).

The development of herbicide-tolerant crops [corn (*Zea mays* L.), soybean (*Glycine max* (L.) Merr.), cotton (*Gossypium hirsutum* L.), and canola (*Brassica napus* L.)] have transformed agricultural production systems by providing chemical options for weed control (Bajwa et al. 2015). However, no such efforts have been made for the development of pearl millet hybrids tolerant to herbicides. Integration of herbicide-tolerant traits combined with drought- and heat-tolerant traits can potentially help pearl millet production rapidly expand across arid and semi-arid regions, even amid changing climates (Kumar et al. 2023a; Todd et al. 2024). Identifying pearl millet parental lines with reduced sensitivity to Acetyl-CoA carboxylase (ACCase) (Group 1) and acetolactate synthase (ALS) (Group 2)-inhibiting POST herbicides may help in developing elite herbicide-tolerant hybrids that can potentially offer grass weed control options. In this context, we initiated a large-scale herbicide screening of advanced pearl millet parental lines developed by the millet breeding program at Kansas State University, Agricultural Research Center, Hays (KSU-ARCH), Kansas. We hypothesized that natural variation may exist among advanced pearl millet parental lines with reduced sensitivity to ACCase (clethodim and quizalofop) and ALS (imazamox and nicosulfuron) inhibiting herbicides. The main objectives of this research were to 1) evaluate the sensitivity of pearl millet parental lines to ACCase (clethodim and quizalofop-p-ethyl - QPE), and ALS (imazamox and nicosulfuron) inhibiting herbicides and 2) characterize the sensitivity levels of selected lines to imazamox and nicosulfuron.

2.3. Materials and Methods

2.3.1. Plant Material

The development of advanced pearl millet parental lines used in this research has previously been described by Ramalingam et al. (2024). In short, by using the recurrent selection method, many selected germplasms were allowed for random mating followed by three election cycles, and the developed advanced lines were sorted out into seed/female parent (B lines) and pollinator/male (R lines) based on the complete sterility and fertility of the test hybrids evaluation in summer 2016 at KSU-ARCH, Kansas. Backcross breeding was followed to develop new seed parent (A - male sterile and B - male fertile/maintainer) inbred lines and simultaneously pedigree breeding was followed for R - restorer inbred lines development between the summer of 2017 and 2020. A total of 56 advanced selected 29B and 27R lines (45 grain and 11 forage types) were used in this study (Table 1).

2.3.2. Single-Dose Bioassays

Greenhouse experiments were conducted in the summer of 2023 and 2024 at the KSU-ARCH, Kansas. Seeds of each line were planted in an individual (28 × 53 × 6 cm) 50-cell plastic tray, filled with a commercial potting mixture (Miracle-Gro Moisture Control Potting Mix, Miracle-Gro Lawn Products). Experiments were laid out in a randomized complete block (blocked by herbicides) design with 50 replications (1 tray = 50 replications). The greenhouse conditions during the study periods were maintained at 32/29°C ± 5 °C day/night with a 15/9 h photoperiod and plants were watered as needed to avoid any moisture stress. Four herbicides, including clethodim (136 g ha^{-1}), QPE (77 g ha^{-1}), imazamox (52 g ha^{-1}), and nicosulfuron (70 g ha^{-1}) were separately evaluated on 56 advanced pearl millet parental lines (Table 2). All selected herbicides were separately applied on all the lines along with crop oil concentrate (1% v/v) at the seedling

stage (3- to 4-leaf stage and 8- to 12-cm tall plants) using a cabinet spray chamber (Research Track Sprayer, De Vries Manufacturing, Hollandale, MN) equipped with an even flat-fan nozzle tip (Tee Jet XR8001E, Spraying System). The spray chamber was calibrated to deliver 139 L ha-1 of the spray solution at 240 kph. After herbicide treatment, all the trays were returned to the greenhouse and were not watered for at least 24 hours.

Data on survival percentage and visual injury (%) of survived plants were recorded at 7, 14, and 21 days after application (DAA) on a scale of 0 to 100%, (where 0= no injury and 100= complete death). The stunting, chlorosis, and/or necrosis of treated pearl millet plants were compared to nontreated) for visual injury evaluation. At 21 DAA, the final number of surviving plants was counted from each tray, and the survival percentage was calculated using the following Equation 1:

$$Survival\ percentage = \left[\frac{Number\ of\ surviving\ plants}{Total\ number\ of\ plants\ treated}\right] * 100$$

A treated plant was considered dead if the plant showed chlorosis, necrosis, and no new regrowth at 21 DAA. The height of 12 surviving plants from each tray were measured from the soil surface to the uppermost extended leaf, and the shoot biomass of those plants were collected and dried at 65 C for five days to measure the shoot dry biomass at 21 DAA. The shoot dry biomass reduction (%) was calculated using the following Equation 2:

$$\text{Shoot dry biomass reduction (\%)} = \left[\frac{C - T}{C}\right] \text{x } 100$$

where C is the shoot dry biomass from the nontreated control plants (average of 12 plants), and T is the shoot dry biomass of a treated plant.

2.3.3 Dose-Response Bioassays

Based on results from single dose bioassays, parental lines with higher survival percentages, percent visual injury, and lower biomass reduction with imazamox (ARCH21B, 35R, 45R, and 49R) and nicosulfuron (ARCH21B, 45R, and 73R) were selected along with one commercial grain sorghum hybrid (P84G62) susceptible to both imazamox and nicosulfuron was included for comparison. Among these selected lines, ARCH21B, 35R, 45R, and 73R were grain whereas 49R was forage type. Separate greenhouse dose-response experiments were conducted and repeated in summer 2023 at the KSU-ARCH, KS to characterize the sensitivity levels of selected parental lines to imazamox and nicosulfuron. Seeds of the selected parental lines were separately planted in 10-by-10 cm squared plastic pots filled with a commercial potting mixture (Miracle-Gro Moisture Control Potting Mix, Miracle-Gro Lawn Products). Experiments were conducted in a randomized complete block (blocked by parental line) design with 12 replications. Greenhouse conditions were the same as followed in the single dose assay. Actively growing seedlings (3 to 4 leaf stage and 8 to 12 cm tall) from each selected pearl millet line were separately treated with various rates of imazamox (0, 13, 26, 52, 104, 208, 416, and 832 g ha^{-1}) and nicosulfuron (0, 17.5, 35, 70, 140, 280, 560, and 1120 g ha^{-1}) along with 1% COC using the same cabinet spray chamber used in the single dose assay screening. After spraying, all treated parental lines were returned back to the greenhouse and watered as needed to avoid any soil moisture stress.

Data on percent visual injury (0 to100%, where 0 = no injury and 100 = complete death) at 7, 14, and 21 DAA were collected. At 21 DAA, the shoot biomass of all treated plants was collected and dried at 65 C for five days to measure shoot dry biomass and the shoot dry biomass reduction (%) was calculated using Equation 2.

2.3.4. Statistical Analysis.

All collected data on visual injury (%), survival (%), and shoot dry biomass reduction (% of nontreated) in both experiments were subjected to analysis of variance (ANOVA) using the PROC MIXED in SAS 9.4 (SAS Institute, Inc., SAS Campus Drive, Cary, NC). The fixed effects in ANOVA were experimental run, herbicides (four herbicides in single dose bioassay and herbicide dose in dose-response bioassay), parental lines, and their interactions. Replications and all interactions involving replication were considered random effects. The data followed all the ANOVA assumptions as tested by the Shapiro-Wilk (P value = 0.342) and Levene (P value = 0.621) tests with the UNIVARIATE and GLM procedures, respectively, with SAS software. The experimental run-by-treatment interaction for single dose and dose-response bioassays was non-significant (P value > 0.05), therefore, data were pooled across experimental runs for each bioassay. For single dose bioassay, the treatment means were compared using Fisher's Protected least significant difference test (P value < 0.05). Data on shoot dry biomass reduction for each tested pearl millet parental line from dose-response bioassays were regressed over imazamox or nicosulfuron doses using a three-parameter nonlinear log-logistic model in R software (Ritz et al. 2015) using the following Equation 3:

$$Y = [\frac{d}{1} + exp\{b\ (log\ x + log\ e)\}]$$

where *Y* is percent shoot biomass reduction, *d* is maximum shoot biomass reduction (upper asymptote, fixed to 100%), *b* is slope, *x* is herbicide dose, and *e* represents imazamox or nicosulfuron dose needed for 50% shoot dry biomass reduction (referred to as GR_{50} values). The Akaike information criterion was used to select the nonlinear three-parameter model. A lack-of-fit test (P > 0.05) was used to confirm that the selected model described the shoot dry biomass reduction of each tested parental line (Ritz et al. 2015). All nonlinear regression parameters and

GR_{90} values (imazamox or nicosulfuron dose required for 90% shoot dry biomass reduction) were estimated using the 'drc' (Analysis of Dose-Response Curves) package (Ritz et al. 2015) in *R* software (R version 4.3.0 Core Team, 2023). The sensitivity index for each selected pearl millet parental line was calculated by dividing the GR_{50} value by the GR_{50} values of the ARCH21B line and SOR.

2.4. Results and Discussion

2.4.1 Single Dose Bioassays

Clethodim

None of the tested pearl millet parental lines survived at 136 g ha^{-1} rate of clethodim with mean visual injury ranging from 95 to 98% and shoot dry biomass reduction from 57 to 95% at 21 DAA (Table 3). These results indicate high sensitivity to clethodim for all screened 56 pearl millet parental lines. Although not reported in pearl millet, clethodim has been found to be highly effective on various grass weed species, including goose grass, bermudagrass, barnyard grass, green foxtail, shattercane, and johnsongrass (Anonymous 2021).

Quizalofop

Among all screened parental lines, only four pearl millet parental lines (ARCH35R, 36R, 50R, and 68R) survived the field use rate of quizalofop (77 g ha^{-1}) with 2 to 12% survival, visual injury of 90 to 95%, and shoot dry biomass reduction of 66 to 95% at 21 DAA (Table 4). The survived plants were transplanted and allowed to set seed in the greenhouse. Further investigations are needed to identify if any quizalofop-tolerant trait is present among these lines. However, recently commercial quizalofop-tolerant crops such as wheat, sorghum, and rice are available in market, and no such trait has been discovered in pearl millet yet. For instance,

quizalofop-resistant winter wheat varieties (CoAXium Wheat Production System) allow growers to use POST-applied quizalofop-p-ethyl herbicide (Ag, Albaugh Company, St. Joseph, MO) for controlling feral rye and other winter annual grass weed species (Kumar et al. 2021). Similarly, sorghum hybrids (Double Team™ sorghum, S&W Sorghum Partners, Longmont, CO) with resistance to quizalofop-p-ethyl (FirstAct™ herbicide, Adama Agricultural Solutions, Ashdod City, Israel) are commercially available for grass weed control (Kumar et al. 2023b). In addition, quizalofop-resistant rice has also been developed through traditional mutation breeding techniques that allows for postemergence applications of quizalofop for grass weed control (Guice et al. 2015).

Imazamox

All 56 advanced pearl millet parental lines survived imazamox (52 g ha^{-1}) at 21 DAA. The survival percentage among these parental lines ranged from 55 to 100% at 21 DAA (Table 5). All parental lines exhibited a high survival percentage ranging from 89 to 100% except for ARCH09B, 21B, 66R, and 16R which showed a survival percentage of 50 to 86% at 21 DAA (Table 5). These results indicate reduced sensitivity to imazamox in all the 56 parental lines. However, the imazamox surviving plants from the most tested parental lines showed a mean visual injury ranging from 20 to 70% at 21 DAA (Table 5). Only five parental lines (ARCH35R, 03B, 04B, 08B, and 70R) had a mean visual injury of 18 to 19% at 21 DAA (Table 5). Consistent with the visual injury (%), the averaged shoot dry biomass reduction (% of nontreated) of imazamox survived plants ranged from 20 to 76% for most of the lines (Table 5). However, the averaged shoot dry biomass reduction of survived plants from nine parental lines (ARCH35R, 49R, 50R, 60R, 73R, 04B, 12B, 15B, and 25B) ranged from 5 to 19%, indicating reduced sensitivity to imazamox (Table 5). Although not reported in pearl millet, the POST

applied imazethapyr at 50 g ha^{-1} has been found highly effective in controlling wild-proso millet (*Panicum miliaceum*) when treated at 1- to 5-leaf stage (Swanton and Chandler 1990).

Nicosulfuron

Similar to imazamox, all advanced parental lines survived the field use rate of nicosulfuron (70 g ha^{-1}) at 21 DAA. Application of nicosulfuron resulted in 70 to 100% survival among all tested parental lines (Table 6). Only three parental lines (ARCH13B, 14B, and 15B) tested with nicosulfuron showed the least survival (70 to 80%) at 21 DAA. Interestingly, these results indicated that most of the tested pearl millet parental lines with reduced sensitivity to imazamox also exhibited reduced sensitivity to nicosulfuron. Mean percent visual injury of survived plants from all these tested parental lines ranged from 20 to 79% at 21 DAA. Only two parental lines (ARCH73R and 08B) had mean visual injury of 13 and 16%. Consistent with the percent survival and visual injury, the average shoot dry biomass reduction (% of nontreated) of the survived plants ranged from 22 to 79% (Table 6). Survived plants from ten parental lines (ARCH65R, 68R, 73R, 04B, 08B, 14B, 15B, 25B, 35B, 36B) had an average

2.4.2. Dose-Response Bioassays

Sensitivity to Imazamox

Based on results of single dose bioassay demonstrated, three selected pearl millet lines (ARCH35R, 45R, and 49R) had reduced sensitivity to imazamox (Table 7). The imazamox dose needed for 50% shoot dry biomass reduction (GR_{50} values) of these three selected lines ranged from 19.3 to 30.6 g ha^{-1}, which was significantly greater than 6.0 g ha^{-1} (SOR) and 2.5 g ha^{-1} (ARCH21B). Furthermore, imazamox dose needed for 90% shoot dry biomass reduction (GR_{90} values) of these three selected lines ranged from 68.3 to 117.5 g ha^{-1}, which was greater than that of SOR (37.4 g ha^{-1}) and ARCH21B (24.5 g ha^{-1}) and the field use rate of imazamox (52 g ha^{-1}).

Based on GR_{50} values, ARCH35R, 45R, and 49R exhibited 3.2 to 12.2 and 7.7 to 12.2-fold reduced sensitivity to imazamox when compared to SOR and ARCH21B, respectively (Table 7; Figure 1). Several studies have previously documented imazamox resistance in wheat, sorghum, rice and grass weed species. Notably, Kumar et al. (2023b) reported 4.1 to 6.0-fold resistance to imazamox in three shattercane (*Sorghum bicolor* L. Moench subsp. drummondii) populations in northwestern Kansas. Domínguez-Mendez et al. (2017) reported 93.7-fold and 43.7-fold resistance to imazamox in wheat cultivars based on Clearfield® technology. Similarly, Kumar and Jha (2017) reported high-level resistance (110.1-fold) to imazamox in downy brome (*Bromus tectorum* L.). More recently, grain sorghum hybrids (igrowth®, Advanta Alta Seeds, Amarillo, TX) tolerant to imazamox are commercially available. These hybrids allow PRE and POST emergence applications of imazamox (IMIFLEX™ herbicide; UPL Company, King of Prussia, PA) for annual grass control (Kumar et al. 2023b).

Sensitivity to Nicosulfuron

Results indicated that both SOR and ARCH21B were effectively controlled by nicosulfuron (37 and 40 g ha^{-1} of nicosulfuron for a 90% reduction in shoot dry biomass, although the recommended field use rate is 70 g ha^{-1}). The ARCH45R and 73R had reduced sensitivity to nicosulfuron (Table 8). The nicosulfuron dose needed for 50% shoot dry biomass reduction (GR_{50} values) of these two selected lines ranged from 18 to 42 g ha^{-1}, which was significantly greater than that of SOR (11 g ha^{-1}) and ARCH21B (7 g ha^{-1}) line. Furthermore, the nicosulfuron dose needed for 90% shoot dry biomass reduction (GR_{90} values) of these two selected lines ranged from 132 to 165 g ha^{-1}, which was greater than that of SOR (37 g ha^{-1}) and ARCH21B (40 g ha^{-1}) and the field use rate of nicosulfuron (70 g ha^{-1}) (Table 8). Based on GR_{50} values,

ARCH45R and 73R exhibited 1.6 to 3.8 and 2.6 to 6-fold reduced sensitivity to nicosulfuron, compared with SOR and ARCH21B, respectively (Table 8; Figure 2). Results from the dose-response studies revealed that the same selected pearl millet line (45R) with a relatively higher sensitivity index (SI) ranging from 3.2- to 7.7-fold for imazamox had a low SI range (1.6 to 2.6-fold) for nicosulfuron compared to the SOR and ARCH21B, respectively. This is a further confirmation for reduced sensitivity to both ALS-inhibiting herbicides. Recently, grain sorghum hybrids with tolerance to nicosulfuron (Inzen™, Corteva Agriscience, Indianapolis, IN) are commercially available. The Inzen™ sorghum allows producers to use POST emergence applications of nicosulfuron (Zest™ WDG herbicide; Corteva Agriscience, Indianapolis, IN) Abit and Al-Khatib (2013). However, there is currently no report on pearl millet hybrid with any herbicide resistance trait.

2.5. Practical Implications

Results from this research discovered a reduced sensitivity to imazamox and nicosulfuron among advanced pearl millet parental lines screened. It is important to know that both forage and grain-type pearl millet lines were evaluated in this study. To our knowledge, this research reports the first case of natural variation of reduced sensitivity to imazamox and nicosulfuron among pearl millet parental lines. However, the underlying mechanism(s) conferring this reduced sensitivity to imazamox and nicosulfuron is unknown and should be investigated. Future studies should also investigate the growth and reproductive fitness of these pearl millet parental lines with reduced sensitivity to imazamox and nicosulfuron.

Pearl millet parental lines with reduced SI for imazamox and nicosulfuron can potentially be utilized for introgression in the development of elite hybrids resistant to ALS-inhibiting herbicides. The development of such elite pearl millet hybrids with reduced sensitivity to ALS-

inhibiting herbicides can allow POST applications of imazamox and nicosulfuron for in-season grass weed control. In this context, the breeding program at KSU-ARCH, KS is currently focusing on developing high-yielding pearl millet hybrids with tolerance to ALS inhibiting herbicides. These hybrids with reduced sensitivity to ALS-inhibiting herbicides may facilitate the adoption and expansion of grain and forage pearl millet by providing POST herbicide options for weed control and can fit into the existing cropping and livestock production system in the central Great Plains drylands.

Based on the dose-response bioassay results, four fresh crosses (Grain: ARCH21B x ARCH35R and ARCH21B x ARCH73R; Forage: ARCH41B x ARCH49R and ARCH41B x ARCH65R) parental lines show in reduced sensitivity for imazamox and nicosulfuron were made in summer 2024 at KSU-ARCH, KS. The main purpose of developing these new crosses is to focus on further development of four bi-parental mapping (mini-nested association mapping) populations by forwarding these four crosses separately from F_1 to F_8 generations to develop recombinant inbred lines (RILs: each cross with 200-250 lines), tag the genomic regions for herbicide tolerance and execute the marker assisted selection (MAS). This approach is an integral part of accelerating classical breeding efforts for the development of high yielding pearl millet hybrids with tolerance to ALS inhibiting herbicides for effective weed control. shoot dry biomass reduction of 0 to 19% at 21 DAA (Table 6).

Table 2.1. List of 56 advanced parental lines of pearl millet used for herbicide screening.

Parent	Type	Lines
Female	Grain	ARCH-01B, 03B, 04B, 05B, 08B, 12B, 13B, 14B, 15B, 16B, 21B, 22B, 24B, 25B, 30B, 31B, 32B, 33B, 35B, 36B, 42B, 44B, 45B, and 47B
	Forage	ARCH-09B, 27B, 37B, 41B, and 46B
Male	Grain	ARCH-26R, 35R, 36R, 45R, 46R, 50R, 60R, 01R, 16R, 21R, 22R, 61R, 62R, 64R, 66R, 67R, 68R, 69R, 73R, 75R, and 76R
	Forage	ARCH-30R, 49R, 63R, 65R, 70R, and 78R

Table 2.2. List of selected POST herbicides used in this study.

Trade name*	Common name	Rate (g ai ha^{-1})	Manufacturer
Select Max	Clethodim	136	Valent
Aggressor	Quizalofop	85	Albaugh Inc.
Beyond	Imazamox	52	BASF
Zest	Nicosulfuron	70	Corteva Agriscience

*All herbicides were applied with crop oil concentrate (COC) at 1% V/V

Table 2.3. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of pearl millet parental lines treated with clethodim at 21 days after application (DAA).

Parental lines	Survival[1]	Visual injury[2]	Shoot dry biomass reduction[2]
	— % —	— % —	— % of nontreated —
Female			
ARCH01B	0	100	82
ARCH03B	0	100	75
ARCH04B	0	100	83
ARCH05B	0	100	83
ARCH08B	0	100	90
ARCH09B	0	100	92
ARCH12B	0	100	87
ARCH13B	0	100	89
ARCH14B	0	100	89
ARCH15B	0	100	91
ARCH16B	0	100	93
ARCH21B	0	100	95
ARCH22B	0	100	84
ARCH24B	0	100	94
ARCH25B	0	100	81
ARCH27B	0	100	40
ARCH30B	0	100	89
ARCH31B	0	100	90
ARCH32B	0	100	90
ARCH33B	0	100	89
ARCH35B	0	100	85
ARCH36B	0	100	89
ARCH37B	0	100	92
ARCH41B	0	100	83
ARCH42B	0	100	79
ARCH44B	0	100	86
ARCH45B	0	100	88
ARCH46B	0	100	95
Male			
ARCH26R	0	100	86
ARCH30R	0	100	89
ARCH35R	0	100	79
ARCH36R	0	100	88
ARCH45R	0	100	89
ARCH46R	0	100	93
ARCH49R	0	100	83
ARCH50R	0	100	95
ARCH60R	0	100	82
ARCH01R	0	100	89

ARCH16R	0	100	57
ARCH21R	0	100	96
ARCH22R	0	100	95
ARCH61R	0	100	97
ARCH62R	0	100	76
ARCH63R	0	100	91
ARCH64R	0	100	92
ARCH65R	0	100	95
ARCH66R	0	100	75
ARCH67R	0	100	93
ARCH68R	0	100	86
ARCH69R	0	100	91
ARCH70R	0	100	95
ARCH73R	0	100	80
ARCH75R	0	100	86
ARCH76R	0	100	94
ARCH78R	0	100	73

[1]Percent survival for each parental line was calculated based on 50 seedlings tested

[2]Percent visual injury and shoot dry biomass reduction (% of nontreated) were recorded from survived seedlings (n =12) in each parental line.

Table 2.4. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of pearl millet parental lines treated with quizalofop at 21 days after application (DAA).

Parental lines	Survival[1]	Visual injury[2]	Shoot dry biomass reduction[2]
	—% —	— %—	— % of nontreated —
Female			
ARCH01B	0	100	82
ARCH03B	0	100	90
ARCH04B	0	100	86
ARCH05B	0	100	89
ARCH08B	0	100	88
ARCH09B	0	100	91
ARCH12B	0	100	89
ARCH13B	0	100	93
ARCH14B	0	100	92
ARCH15B	0	100	86
ARCH16B	0	100	95
ARCH21B	0	100	86
ARCH22B	0	100	85
ARCH24B	0	100	98
ARCH25B	0	100	72
ARCH27B	0	100	94
ARCH30B	0	100	83
ARCH31B	0	100	92
ARCH32B	0	100	90
ARCH33B	0	100	84
ARCH35B	0	100	90
ARCH36B	0	100	88
ARCH37B	0	100	95
ARCH41B	0	100	66
ARCH42B	0	100	88
ARCH44B	0	100	90
ARCH45B	0	100	77
ARCH46B	0	100	94
ARCH26R	0	100	89
Male			
ARCH30R	0	100	81
ARCH35R	3	95	83
ARCH36R	2	95	85
ARCH45R	0	100	88
ARCH46R	0	100	94

ARCH49R	0	100	86
ARCH50R	12	90	87
ARCH60R	0	100	90
ARCH01R	0	100	84
ARCH16R	0	100	77
ARCH21R	0	100	95
ARCH22R	0	100	95
ARCH61R	0	100	85
ARCH62R	0	100	79
ARCH63R	0	100	91
ARCH64R	0	100	70
ARCH65R	0	100	89
ARCH66R	0	100	76
ARCH67R	0	100	92
ARCH68R	5	95	86
ARCH69R	0	100	92
ARCH70R	0	100	90
ARCH73R	0	100	95
ARCH75R	0	100	87
ARCH76R	0	100	95
ARCH78R	0	100	94

[1]Percent survival for each parental line was calculated based on 50 seedlings tested

[2]Percent visual injury and shoot dry biomass reduction (% of nontreated) were recorded from survived seedlings (n =12) in each parental line.

Table 2.5. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of pearl millet parental lines treated with imazamox at 21 days after application (DAA).

Parental lines	Survival[1]	Visual injury[2]	Shoot dry biomass reduction[2]
	—% —	— %—	— % of nontreated —
Female			
ARCH01B	95	40 e	61
ARCH03B	100	19 d	20
ARCH04B	100	17 e	19
ARCH05B	98	38 e	40
ARCH08B	100	19 c	25
ARCH09B	55	25 b	50
ARCH12B	98	28 d	15
ARCH13B	92	25 e	27
ARCH14B	98	40 c	41
ARCH15B	98	26 d	10
ARCH16B	100	33 e	39
ARCH21B	80	50 d	76
ARCH22B	97	28 a	20
ARCH24B	100	42 d	28
ARCH25B	98	33 c	14
ARCH27B	98	38 d	30
ARCH30B	90	44 e	53
ARCH31B	93	49 d	49
ARCH32B	100	37 c	47
ARCH33B	95	50 c	58
ARCH35B	90	30 c	36
ARCH36B	98	28 d	25
ARCH37B	89	25 d	41
ARCH41B	86	56 c	57
ARCH42B	94	33 e	40
ARCH44B	100	28 d	20
ARCH45B	94	72 e	62
ARCH46B	100	45 d	39
ARCH47B	92	55 d	62
Male			
ARCH26R	100	26 c	66
ARCH30R	100	28 c	46
ARCH35R	100	18 d	14
ARCH36R	100	20 b	26
ARCH45R	100	36 a	31

ARCH46R	100	21 d	20
ARCH49R	100	20 b	5
ARCH50R	100	29 d	10
ARCH60R	98	30 c	19
ARCH01R	100	27 d	36
ARCH16R	86	33 d	42
ARCH21R	91	36 b	45
ARCH22R	100	37 b	57
ARCH61R	98	31 e	26
ARCH62R	98	28 d	39
ARCH63R	96	37 e	45
ARCH64R	100	37 d	24
ARCH65R	100	38 b	28
ARCH66R	84	43 e	33
ARCH67R	94	34 d	46
ARCH68R	97	64 d	60
ARCH69R	93	37 c	65
ARCH70R	89	19 c	25
ARCH73R	100	33 e	18
ARCH75R	98	51 d	56
ARCH76R	98	44 c	53
ARCH78R	96	43 d	54

[1]Percent survival for each parental line was calculated based on 50 seedlings tested.

[2]Percent visual injury and shoot dry biomass reduction (% of nontreated) were recorded from survived seedlings (n =12) in each parental line.

Table 2.6. Percent survival, visual injury, and shoot dry biomass reduction (% of nontreated) of Pearl millet parental lines treated with nicosulfuron 21 days after application (DAA).

Parental lines	Survival[1]	Visual injury[2]	Shoot dry biomass reduction[2]
Males	— % —	— % —	— % of nontreated —
ARCH26R	100	22 d	44
ARCH30R	93	23 e	39
ARCH35R	100	21 d	22
ARCH36R	100	31 d	26
ARCH45R	100	79 b	76
ARCH46R	92	61 d	59
ARCH49R	97	23 a	29
ARCH50R	100	30 d	31
ARCH60R	100	52 d	80
ARCH01R	100	46 d	77
ARCH16R	94	27 d	45
ARCH21R	100	66 d	77
ARCH22R	100	50 e	22
ARCH61R	98	22 e	23
ARCH62R	100	33 d	29
ARCH63R	100	20 e	47
ARCH64R	97	39 d	35
ARCH65R	98	29 e	12
ARCH66R	98	44 e	41
ARCH67R	100	25 e	39
ARCH68R	95	23 d	8
ARCH69R	97	26 e	48
ARCH70R	96	20 e	28
ARCH73R	100	13 e	0
ARCH75R	97	41 e	62
ARCH76R	98	30 e	43
ARCH78R	100	52 e	59
Females			
ARCH01B	96	37 e	26
ARCH03B	100	23 d	42
ARCH04B	98	36 e	11
ARCH05B	94	23 e	47
ARCH08B	96	16 d	10
ARCH09B	94	39 a	24

ARCH12B	100	32 e	27
ARCH13B	80	34 d	23
ARCH14B	70	26 e	15
ARCH15B	77	35 e	10
ARCH16B	98	70 e	47
ARCH21B	90	39 a	79
ARCH22B	91	35 d	24
ARCH24B	100	20 e	27
ARCH25B	100	22 d	0
ARCH27B	96	48 d	32
ARCH30B	96	37 d	56
ARCH31B	91	20 d	60
ARCH32B	96	28 c	30
ARCH33B	98	23 b	43
ARCH35B	94	20 d	10
ARCH36B	95	43 d	19
ARCH37B	92	45 c	64
ARCH41B	95	38 b	64
ARCH42B	97	28 e	46
ARCH44B	96	40 c	41
ARCH45B	98	37 d	62
ARCH46B	94	39 d	40
ARCH47B	90	37 d	44

[1]Percent survival for each parental line was calculated based on 50 seedlings tested.

[2]Percent visual injury and shoot dry biomass reduction (% of nontreated) were recorded from survived seedlings (n =12) in each parental line.

Table 2.7. Regression estimates of the 3-parameter log-logistic equation fitted to shoot dry biomass reduction (% of nontreated) of selected pearl millet parental lines sprayed with different imazamox doses 21 days after application (DAA).

	Parameter estimates (± SE)[2]							
Parental lines[1]	*d*	*b*	GR_{50} (g ha^{-1})	95% CI	SI (SOR)[3]	SI (21B)[4]	GR_{90}[5] (g ha^{-1})	95% CI
ARCH45R	75 (1.6)	2.1 (2.6)	19.3	16-22	3.2	7.7	79.3	45-113
ARCH35R	74 (1.6)	1.5 (2.1)	24.7	22-28	4.1	9.8	68.3	48-89
ARCH49R	71 (1.9)	1.6 (2.1)	30.6	26-35	12.2	12.2	117.5	66-169
ARCH21B	85 (2.4)	9.7 (5.7)	2.5	0-8	-	-	24.5	0-48
SOR	88 (2.0)	1.2 (2.8)	6.0	2-10	-	-	37.4	10-64

[1]ARCH21B = highly sensitive pearl millet line; ARCH45R, 35R, and 49R = least sensitive pearl millet parental lines SOR = commercial sorghum check hybrid

[2]*d* is the upper limit, *b* is the slope of each dose-response curve with standard error in parentheses, and GR_{50} is the effective dose of imazamox needed for 50% shoot dry biomass reduction (% of nontreated) for each tested line

[3]SI (SOR) is the ratio of the GR_{50} value of each least sensitive pearl millet line relative to that of the GR_{50} value of the sorghum check hybrid

[4]SI (21B) is the ratio of the GR_{50} value of each least sensitive pearl millet line relative to that of GR_{50} value of highly sensitive ARCH21B line

[5]GR_{90} is the effective dose (g ha^{-1}) of imazamox needed for 90% shoot dry biomass reduction (% of nontreated) for each parental line

CI, confidence interval

Table 2.8. Regression estimates of the 3-parameter log-logistic equation fitted to shoot dry biomass reduction (% of nontreated) of selected pearl millet lines sprayed with different nicosulfuron doses 21 days after application (DAA).

Parental lines[1]	Parameter estimates (± SE)[2]			95% CI	SI (SOR)[3]	SI (21B)[4]	GR_{90}[5] (g ha^{-1})	95% CI
	d	*b*	GR_{50} (g ha^{-1})					
ARCH45R	81.1 (2.0)	1.1 (0.1)	18	15-22	1.6	2.6	132	50-213
ARCH73R	69.5 (1.7)	1.6 (0.1)	42	36-49	3.8	6	165	98-231
ARCH21B	82.4 (1.4)	1.2 (0.4)	7	2-12	-	-	40	17-63
SOR	98.2 (1.1)	1.8 (0.3)	11	9-15	-	-	37	26-48

[1]SOR = commercial sorghum hybrid; ARCH21B = highly sensitive pearl millet line; ARCH45R and 73R = least sensitive pearl millet parental lines

[2]*d* is the upper limit, *b* is the slope of each dose-response curve with standard error in parentheses, and GR_{50} is the effective dose (g ha^{-1}) of nicosulfuron needed for 50% shoot dry biomass reduction (% of nontreated) for each tested line

[3]SI (SOR) is the ratio of GR_{50} value of each least sensitive pearl millet line relative to that of GR_{50} value of the commercial sorghum check hybrid

[4]SI (21B) is the ratio of GR_{50} value of each least sensitive line relative to that of GR_{50} value of highly sensitive ARCH21B line

CI, confidence interval

[5]GR_{90} is the effective dose (g ha^{-1}) of nicosulfuron needed for 90% shoot dry biomass reduction (% of nontreated) for each line

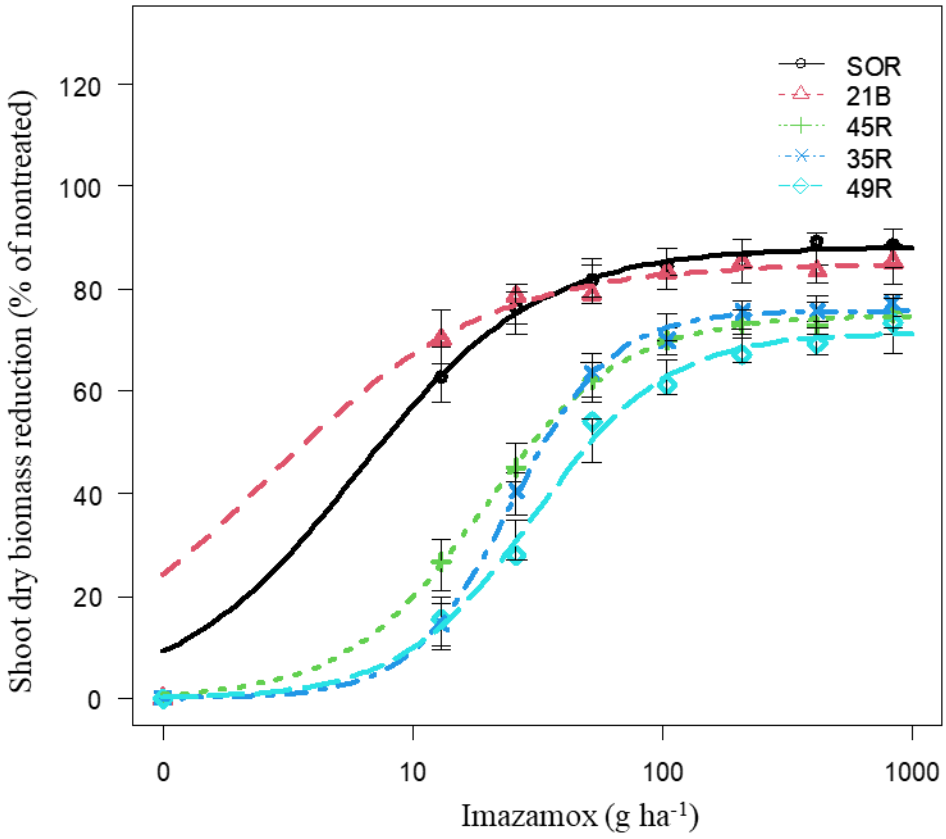

Figure 2.1. Shoot dry biomass reduction (% of nontreated) of pearl millet parental lines and commercial sorghum hybrid treated with different doses of imazamox at 21 days after application (DAA).

Symbols indicate actual values of shoot dry biomass (% of nontreated), and lines indicate predicted values of shoot dry biomass (% of nontreated) obtained from the three-parameter log-logistic model. Vertical bars indicate model-based standard errors (plus and minus) of the predicted mean. SOR = commercial sorghum hybrid; ARCH21B = highly sensitive line; ARCH45R, 35R, and 49R = least sensitive lines.

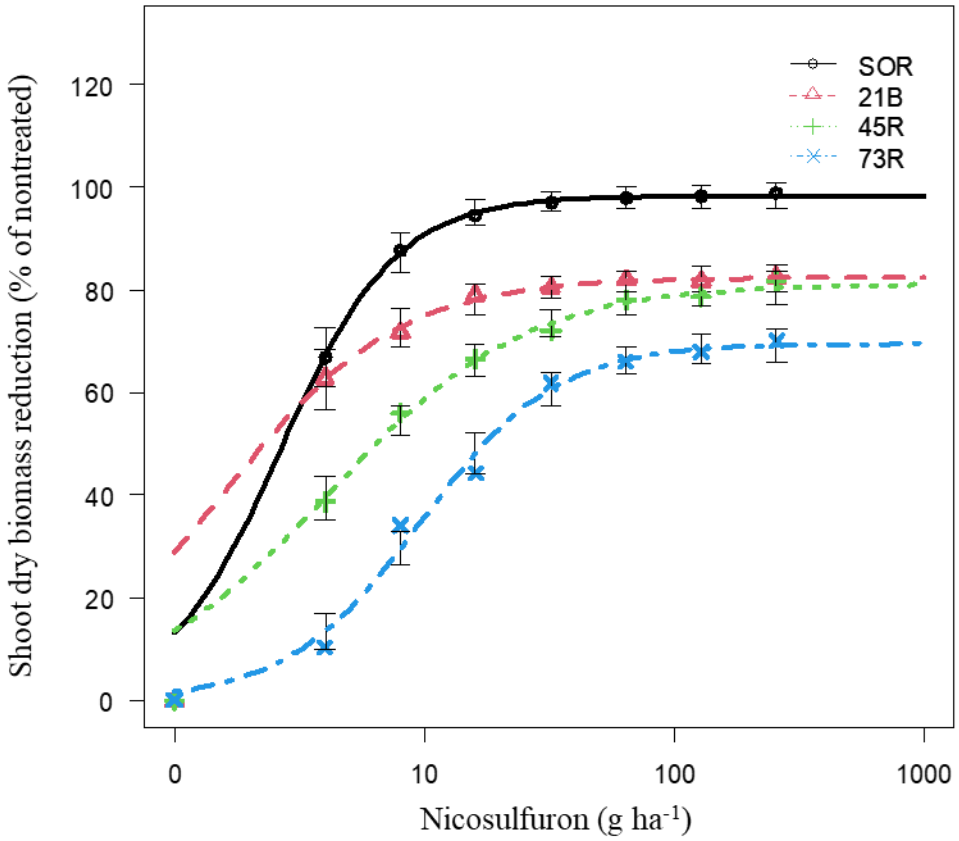

Figure 2.2. Shoot dry biomass reduction (% of nontreated) of selected pearl millet parental lines and conventional sorghum hybrid treated with various doses of nicosulfuron at 21 days after application (DAA).

Symbols indicate actual values of shoot dry biomass reduction (% of nontreated), and lines indicate predicted values of shoot dry biomass reduction (% of nontreated) obtained from the three-parameter log-logistic model. Vertical bars indicate model-based standard errors of the predicted mean. SOR = commercial sorghum hybrid; 21B = highly sensitive ARCH21B line; 45R and 73R = least sensitive ARCH45R and 73R lines.

Chapter 3 - Pearl Millet [*Pennisetum glaucum* (L.) R. Br.] Hybrids Tolerance and Weed Control with Preemergence Herbicides

3.1. Abstract

Weed management is a major production challenge in pearl millet. Limited herbicide options labeled for use in pearl millet further complicates weed control. To fill this knowledge gap, field experiments were conducted during 2023 and 2024 growing seasons at Kansas State University (KSU) Agricultural Research Center in Hays, Kansas, to investigate eight preemergence (PRE) herbicides (labeled in sorghum) for crop safety and weed control in three pearl millet hybrids. Averaged across two growing seasons, PRE-applied *S*-metolachlor alone or in combinations with atrazine, mesotrione, or atrazine + mesotrione was injurious (>95% injury) to all three pearl millet hybrids at 28 days after application (DAA). Visual injury with acetochlor + atrazine ranged from 50 to 96% across hybrids. Atrazine or mesotrione applied alone or in combinations were safe (injury < 5%) on all hybrids. All tested PRE herbicides provided effective control (≥ 90%) of Palmer amaranth at 28 DAA, except *S*-metolachlor (86%) in all three hybrids. The highest green foxtail control (≥ 99%) was achieved with mesotrione and acetochlor in combination with atrazine at 28 DAA. All three hybrids recorded the highest grain yields (4370 to 5873 kg ha^{-1}) with atrazine, mesotrione, and their combination. These results suggest that pre-applied atrazine, mesotrione, or premixture of atrazine + mesotrione may be safely used for Palmer amaranth and green foxtail control in pearl millet hybrids.

Nomenclature: Acetochlor; atrazine; *S*-metolachlor; mesotrione; foxtail, *Setaria viridis* (L.) Beauv.; Palmer amaranth, *Amaranthus palmeri* S. Watson; Pearl millet [*Pennisetum Glaucum* (L.) R. Br.]

Keywords: Central Great Plains; Herbicide tolerance; Residual weed management

3.2. Introduction

Pearl millet is one of the most important climate-resilient crops that can potentially sustain food and nutrition security in arid and semiarid regions (Perumal et al. 2024; Satyavathi et al. 2021). Around the world, pearl millet is the 6th most important cereal crop after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum bicolor* L. Moench) (Satyavathi et al. 2021). Pearl millet is a staple crop for more than 90 million people in Africa and the Indian subcontinent, providing food, feed, and fuel worldwide (Daduwal et al. 2024). The global pearl millet production in 2024 was 31 million tons (MT) and India ranked first by producing 13 MT, contributing 43% of the total global production (USDA 2024). Pearl millet is widely grown for grazing, hay, cover crops, feed, and fodder, with roughly 1.5 million acres under production in the U.S. (Myers 2002; Iowa Extension and Outreach 2020). It is recognized as a potential forage and feed crop that is well-suited for double cropping in the U.S. (Wilson et al. 1996). In comparison to other major cereals, pearl millet has high nutritional values. It is a good source of energy, carbohydrates, proteins (8 to 19%), and fat (3 to 8%), and minerals (2.3 mg per 100 g), including iron and zinc, potassium, phosphorus, and vitamins like riboflavin, niacin, and thiamine (Satyavathi et al. 2021; Uppal et al. 2015). Pearl millet has enormous potential to culminate micronutrient deficiencies in developing countries and improve human nutrition and health (Rai et al. 2012).

Among cereals, pearl millet is highly water-use efficient and can tolerate high heat stress (Nambiar et al. 2011; Prasad et al. 2017). It has a C_4 photosynthetic pathway, enhancing its carbon fixation efficiency and growth in adverse environmental condition. This adaptive

mechanism is key to its growth and productivity, under drought or high-temperature stress conditions (Daduwal et al. 2024; Howarth et al. 1996). Pearl millet can produce grain and fodder in dry and hot climates and on marginal soils (which are unsuitable for sorghum and corn) further highlighting its potential as a climate-resilient crop in the Central Great Plains (CGP) region (Kumar et al. 2023).

Weed management poses a serious production challenge in pearl millet (Kumar et al. 2023). Pearl millet is relatively a poor competitor with weeds due to its slow growth early in the season, which can result in substantial yield losses (Cook et al. 2005). Critical period of weed control (CPWC) in pearl millet ranges from 28 to 42 days after planting (Chaudhary et al. 2018). Major predominant weed species in pearl millet growing region in the CGP include Palmer amaranth (*Amaranthus palmeri* S. Watson), redroot pigweed (*Amaranthus retroflexus* L.), kochia (*Bassia scoparia* (L.) A. J. Scott), green foxtail (*Setaria viridis* (L.) P. Beauv.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), giant foxtail (*Setaria faberi* Herrm) and Johnsongrass (*Sorghum halepense* (L.) Pers.) (Kumar et al. 2023). Season-long interference from both grass and broadleaf weed species at various densities can reduce pearl millet grain yields by 16 to 94% (Balyan et al. 1993; Das and Yaduraju 1995; Sharma and Jain 2003).

Limited herbicide options with a potentially narrow selectivity range between annual grass weeds and pearl millet are major constraints in developing effective chemical-based weed control strategies (Dowler and Wright 1995; Mishra 2015). The lack of pre or postemergence (POST) herbicides labeled in pearl millet is one of the major concerns for most of the producers. Widespread evolution of herbicide-resistant weed biotypes across various regions further exacerbates the problem of weed control in pearl millet (Heap 2025). In addition, information on the performance of various preemergence herbicides for crop safety and weed control in pearl

millet is lacking. In this context, we initiated field studies to evaluate the effectiveness of different preemergence herbicides (labeled in sorghum) for crop safety and weed control in advanced pearl millet hybrids developed at Kansas State University. We hypothesized that preemergence herbicides labeled in sorghum could provide crop safety and effective weed control in pearl millet, as sorghum and pearl millet belong to the same family 'Poaceae'. Therefore, the main objectives for this study were to 1) determine the tolerance of pearl millet hybrids to preemergence herbicides, 2) evaluate the effectiveness of preemergence herbicides for weed control in pearl millet, and 3) determine the impact of preemergence herbicides on pearl millet grain yields.

3.3. Material and Methods

3.3.1. Pearl Millet Hybrids

The advanced pearl millet parental lines initially developed at Kansas State University Agricultural Research Center in Hays (KSU-ARCH) were used to develop pearl millet hybrids in the summer of 2022 and 2023 (Ramalingam et al. 2024; Serba et al. 2017). Three hybrids (Hyb1: ARCH-32A/ARCH-21R; Hyb2: ARCH-37A/ARCH-49R and Hyb3: ARCH-41A/ARCH-70R) developed by the millet breeding program at KSU-ARCH were used in this investigation.

3.3.2. Field Experiment

Field studies were conducted in the summer of 2023 and 2024 at the KSU-ARCH, Kansas. The soil type at the study site (38.86201° N, 99.33461° W) was Roxbury silt loam, with a pH of 7.6 and organic matter of 2.1%. Information on various preemergence herbicides, their rates, and manufacturers is summarized in Table 1. A nontreated weedy check was included for comparisons of preemergence herbicides for each pearl millet hybrid. Mean monthly air

temperatures and total monthly precipitation during the study periods are summarized in Table 2 and were recorded from the Kansas State University Mesonet weather station (https://mesonet.kstate.edu). The study sites were historically under a conventionally tilled sorghum-fallow rotation for >5 yrs and had a uniform infestation of Palmer amaranth and green foxtail. Each yr, the study site was tilled, and fine seedbed was prepared prior to the planting of pearl millet hybrids. Each pearl millet hybrid was planted using 172,149 seeds ha^{-1} in rows spaced 76 cm apart on June 16 in both yrs. All selected preemergence herbicides were applied immediately after planting of pearl millet hybrids using a CO_2-operated backpack sprayer equipped with flat-fan 110015XR nozzles (TeeJet Technologies, Glendale Heights, IL). The sprayer was calibrated to deliver a spray solution at a rate of 140 L ha^{-1}, maintaining a consistent pressure of 276 kPa. A supplemental irrigation of 2.5 cm was applied using a sprinkler irrigation system on June 17, 2024, whereas no irrigation was applied in 2023. Treatments were laid out in a split-plot (hybrid as a main plot and herbicides as a sub-plot) randomized complete block design with 3 replications (each plot 1.5 m wide and 3 m long). All standard agronomic practices on pearl millet production, including time of planting, seeding rate, nutrient and pest management practices were followed as recommended by agronomist at Kansas State University.

3.3.4. Data Collection

Pearl millet stand counts were determined from each plot at 7 and 14 days after application (DAA) of preemergence herbicides by counting the number of plants per meter of row. Percent visual injury on a scale of 0 to 100% (where 0 = no injury and 100 = complete death) was assessed at 7, 14, 28, and 56 DAA. Similarly, visual control ratings of Palmer amaranth and green foxtails were collected at 7, 14, 28, and 56 DAA. Total weed biomass with

individual densities of Palmer amaranth and green foxtails were also recorded at 28, and 56 DAA using one square meter quadrat from the center of each plot. The harvested weed biomass from each plot was oven-dried at 65 °C for 7 days to determine the aboveground shoot biomass. Plants of each pearl millet hybrid were manually harvested from one meter row from the middle two rows of each plot at maturity. Harvested plants were dried in an oven at 65 °C for 7 days and grain heads were threshed using a millet thresher (BT-14 Single Plant Belt Thresher, ALMACO, Nevada, Iowa) and weighed to estimate the grain yield (kg ha^{-1}) of each pearl millet hybrid.

3.3.5. Statistical Analyses

Due to non-significant yr-by-treatment interaction (P = 0.472), all data were pooled across both yrs. Pooled data were checked for analysis of variance (ANOVA) assumptions using PROC UNIVARIATE and PROC MIXED in SAS. Data on percent visual injury, weed control, weed density and total weed biomass were log-transformed to improve the normality of the residuals and homogeneity of variance; however, back-transformed data were presented with mean separation based on the transformed data. Pooled data were subjected to ANOVA using the GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC) to test the significance of the fixed effects. The fixed effects in ANOVA were PRE herbicides, pearl millet hybrids, and their interactions. Replications and all interactions involving replication were considered random effects. Means were separated using the Fisher's protected LSD test at $\alpha = 0.05$.

3.4. Results and Discussion

The amount and timing of precipitation relative to preemergence herbicide applications differed in both yrs (Table 2). A precipitation event (1 to 2 cm) is generally required for the

activation of soil applied herbicides (Parker 1966). In 2023 growing season, preemergence herbicides were applied immediately after pearl millet planting and the precipitation event (2.5 cm) occurred on the same day. In the 2024 growing season, supplemental irrigation (2 cm) was applied immediately after pearl millet planting and preemergence herbicides application. Total monthly precipitation ranged from 17 to 95 mm in 2023 and 6 to 111 mm in 2024 during experimental periods (Table 2). Mean monthly air temperature ranged from 14 to 26 °C in 2023 and 17 to 26 °C in 2024 during the experimental period (Table 2).

3.4.1. Percent Visual Injury

A significant interaction (P = 0.0215) between pearl millet hybrids and tested PRE herbicides was observed for percent visual injury (Table 3). Injury was observed in the form of stand loss, plant stunting, leaf chlorosis, bleaching, and necrosis of leaves. Averaged across both yrs, preemergence applied atrazine or mesotrione alone or in combination of both exhibited the least injury (0 to 3%) on all three hybrids at 28 and 56 DAA (Table 3). However, a variable injury was observed with acetochlor + atrazine applied PRE throughout the growing season with 50%, 67% and 96% injury on Hyb3, Hyb2, and Hyb1, respectively, at 28 DAA. A similar response was observed with 33%, 43% and 92% injury on Hyb3, Hyb2, and Hyb1, respectively, at 56 DAA. Among all tested herbicides, PRE applied *S*-metolachlor alone or in combination with atrazine or atrazine + mesotrione was highly injurious (90 to 97%) to all three hybrids (Table 3). Dowler and Wright (1993) previously reported 95 to 100% injury on pearl millet with PRE applied metolachlor in Florida and Georgia. Furthermore, Cuerrier et al (2009) reported a significant reduction in plant density and yield of grain and forage pearl millet with PRE applied *S*-metolachlor/ benoxacor in Canada. Chloroacetanilide herbicides including acetochlor and *S*-

metolachlor are known to cause significant phototoxicity and reduce yields in proso millet (*Panicum miliaceum* L.) (Jia et al. 2022). These results clearly indicate that PRE applied *S*-metolachlor alone or *S*-metolachlor containing herbicide premixes are injurious to pearl millet.

3.4.2. Weed Control, Density, and Biomass

3.4.2.1. Palmer amaranth control

In general, all preemergence herbicides tested were effective in controlling Palmer amaranth across both growing seasons. Averaged across hybrids, PRE applied mesotrione and acetochlor + atrazine provided the highest control (97% to 99%) of Palmer amaranth throughout the growing season which did not differ from atrazine + mesotrione (Table 4). These results are consistent with Hay et al. (2019), who reported 99% control of atrazine-resistant Palmer amaranth at 60 DAA with PRE applied acetochlor + atrazine in double-cropped grain sorghum in Kansas. Similarly, PRE applied atrazine + mesotrione resulted in 97% control of atrazine-resistant Palmer amaranth at 45 days after corn planting in Michigan (Kohrt and Sprague 2017). In the current study, PRE applied atrazine alone or in combination with *S*-metolachlor or *S*-metolachlor + mesotrione resulted in ≥ 91% control of Palmer amaranth at 56 DAA (Table 4). Previously, Currie and Geier (2016) reported ≥ 90% control of Palmer amaranth at 71 DAA with PRE applied acetochlor + atrazine and *S*-metolachlor + atrazine + mesotrione in sorghum. Similarly, Janak and Grichar (2016) reported 92% to 99% control of Palmer amaranth up to 109 days after PRE application of *S*-metolachlor + atrazine + mesotrione. In contrast, Hay et al. (2019) reported only 72% control of atrazine-resistant Palmer amaranth at 60 DAA of PRE applied atrazine alone. It is important to note that atrazine rate tested in the current study was 2260 g ha^{-1} as compared to 1680 g ha^{-1} tested by Hay et al. (2019). Control with PRE applied *S*-

metolachlor was 99% control at 14 DAA, which later declined to 86% at 56 DAA in the current study. These results are consistent with Starkey (2015), who reported >90% control of Palmer amaranth 60 DAA with mesotrione or *S*-metolachlor + mesotrione. In that study, Palmer amaranth control with PRE applied *S*-metolachlor was 99% at 30 DAA but declined to 70% at 60 DAA (Starkey 2015).

3.4.2.2. Green foxtail control

Consistent with Palmer amaranth, majority of the tested PRE herbicides were also effective in controlling green foxtail across both growing seasons. Averaged across hybrids, PRE applied acetochlor + atrazine resulted in complete control of green foxtail throughout both growing seasons (Table 4). However, Armel et al. (2003) reported 85 to 91% control of giant foxtails (*Setaria faberi*) (a closely related species)) at 60 DAA in corn with PRE applied acetochlor + atrazine. In current study, PRE applied atrazine alone or in combinations with mesotrione or *S*-metolachlor + mesotrione provided up to 98% control of green foxtail (Table 4). Furthermore, PRE applied atrazine alone or in combination with *S*-metolachlor or *S*-metolachlor + mesotrione resulted in 93 to 95% control of green foxtail (Table 4). These results are consistent with Buhler (1991), who reported 91% to 97% control of giant foxtail at 60 DAA with PRE applied atrazine + metolachlor in chisel-plow or no-till corn. These results are contrary to Currie and Geier (2016), who reported only 75 to 83% control of green foxtail at 71 DAA with PRE applied acetochlor + atrazine and *S*-metolachlor + atrazine + mesotrione in grain sorghum.

3.4.3. Weed Density

3.4.3.1. Palmer amaranth density

Consistent with percent visual control, all PRE herbicides resulted in significant reduction of Palmer amaranth density as compared to nontreated weedy check. For instance, PRE applied mesotrione, atrazine + mesotrione, and acetochlor + atrazine significantly reduced Palmer amaranth density (1 to 2 plants m^{-2}) as compared to nontreated weedy check (14 plants m^{-2}) at 28 DAA (Table 5). Similarly, PRE applied atrazine or *S*-metolachlor alone or in combination and *S*-metolachlor + mesotrione were equally effective in reducing Palmer amaranth density (4 to 5 plants m^{-2}) as compared to nontreated weedy check at 28 DAA (Table 5). Compared to nontreated weedy check (15 plants m^{-2}), the highest reduction in Palmer amaranth density (1 to 3 plants m^{-2}) was observed with PRE applied mesotrione and *S*-metolachlor + mesotrione at 56 DAA, which did not differ from atrazine + mesotrione, acetochlor + atrazine, and atrazine + *S*-metolachlor + mesotrione. Furthermore, Palmer amaranth density at 56 DAA of PRE applied atrazine, s-metolachlor, and atrazine + s-metolachlor ranged from 4 to 5 plants m^{-2} (Table 5). These results are consistent with Hay et al. (2019), who previously reported significant reduction in atrazine-resistant Palmer amaranth density (0.01 to 1.45 plants m^{-2}) with PRE applied atrazine, acetochlor + atrazine, atrazine + *S*-metolachlor and atrazine + *S*-metolachlor + mesotrione at 60 DAA as compared to nontreated weedy check (10.9 plants m^{-2}) in double-cropped sorghum.

3.4.3.2. Green foxtail density

Consistent with visual control, all tested PRE herbicides significantly reduced green foxtail density at 28 and 56 DAA compared to nontreated weedy check. For instance, PRE applied mesotrione, atrazine + mesotrione, and atrazine + s-metolachlor + mesotrione completely reduced green foxtail density at 28 DAA, which did not differ from atrazine, atrazine + s-

metolachlor, acetochlor + atrazine. Similarly, PRE applied s-metolachlor and s-metolachlor + mesotrione significantly reduced green foxtail density (3 to 4 plants m^{-2}) as compared to nontreated weedy check (7 plants m^{-2}). Compared to nontreated weedy check (10 plants m^{-2}), PRE applied atrazine, s-metolachlor, mesotrione or atrazine + s-metolachlor, atrazine + mesotrione, acetochlor + atrazine, and atrazine + s-metolachlor + mesotrione significantly reduced green foxtail density (0 to 3 plants m^{-2}) at 56 DAA (Table 5). Similarly, Buhler (1991) reported significant reductions in giant foxtail density at 60 DAA with PRE applied atrazine + metolachlor (2 to 16 plants m^{-2}) as compared to nontreated weedy control (108 to 145 plants m^{-2}) in chisel-plow or no-till corn. The least reduction in green foxtail density (5 plants m^{-2}) was observed at 56 DAA with PRE applied s-metolachlor + mesotrione at 60 DAA as compared to the nontreated weedy check in double-cropped sorghum (Table 5).

3.4.4. Total weed biomass

Among all herbicides tested, PRE applied mesotrione, atrazine + mesotrione, or acetochlor + atrazine significantly reduced total weed biomass (2 to 6 g m^{-2}) at 28 DAA as compared to nontreated weedy check (49 g m^{-2}) (Table 5). Furthermore, PRE applied atrazine, atrazine + *S*-metolachlor, or *S*-metolachlor + mesotrione resulted in lower weed biomass (10 to 14 g m^{-2}) at 28 DAA. Compared to nontreated weedy check (82 g m^{-2}), all tested PRE herbicides significantly reduced total weed biomass (14 to 24 g m^{-2}) at 56 DAA (Table 5). These results are consistent with Hay et al. (2019), who reported significant reduction in aboveground biomass (1 to 42 g m^{-2}) of atrazine-resistant Palmer amaranth with PRE applied atrazine + *S*-metolachlor, acetochlor + atrazine, and *S*-metolachlor + mesotrione + atrazine as compared to nontreated weedy check (191 g m^{-2}).

3.4.5. Grain Yield

Averaged across all three hybrids, the observed grain yields with various PRE herbicides were consistent with pearl millet injury and weed control. Season-long weed interference in nontreated check resulted in grain yield of 3,415 to 3,654 kg ha^{-1} across three hybrids. Among all tested PRE herbicides, atrazine + mesotrione resulted the highest grain yield across three hybrids (5,254 to 5,873 kg ha^{-1}) (Table 6). Grain yields of all three hybrids ranged from 4,370 to 4,687 kg ha^{-1} with PRE applied atrazine and 5,047 to 5,250 kg ha^{-1} with PRE applied mesotrione alone (Table 6). PRE applied acetochlor + atrazine resulted in variable grain yields (1,526 to 3829 kg ha^{-1}) of three tested hybrids. Consistent with visual injury, PRE applied *S*-metolachlor alone or any *S*-metolachlor containing premixes significantly reduced grain yield (106 to 296 kg ha^{-1}) across three hybrids (Table 6).

3.5. Practical Implications

The study provides key insights into the tolerance of pearl millet hybrids to various PRE herbicides (labeled in grain sorghum) and their effectiveness on weed control. Results suggest that PRE applied atrazine or mesotrione alone or atrazine + mesotrione were safer on all three hybrids and provided an excellent control of Palmer amaranth and green foxtail (> 95%) throughout the growing season. In contrast, PRE-applied *S*-metolachlor alone or in combination with atrazine, mesotrione, or atrazine + mesotrione were effective in controlling Palmer amaranth and green foxtails but exhibited significant injury (93 to 97%) on all three hybrids. It is important to note that the tested PRE herbicides in this study are currently not labeled for use in pearl millet and information gained from this current study may further help in the registration of

these PRE herbicides for use in pearl millet. A variable injury response of pearl millet hybrids to PRE applied acetochlor + atrazine further suggests that hybrid selection may play a crucial role in herbicide tolerance. These results provide effective PRE herbicide options for pearl millet; however, effective POST herbicide options for crop safety and weed control in pearl millet are further warranted. Future research should also focus on the development of integrated weed control tactics (chemical and non-chemical) in pearl millet. In addition, research on multiple locations considering broader environmental and soil conditions and commercial hybrids under on-farm conditions will be important and may further help with registrations of these herbicides in pearl millet

Table 3.1. List of selected preemergence herbicides, rates, adjuvants, and manufacturers tested on the pearl millet hybrids.

Trade name	Common name	Rates	Adjuvant	Manufacturer
		g ha^{-1}		
Atrazine 4L	Atrazine	2240	-	Loveland Products, Inc.
Dual ll Magnum	S-metolachlor	1740	-	Syngenta Crop Protection, LLC
Callisto	Mesotrione	210	COC	Syngenta Crop Protection, LLC
Bicep ll Magnum	Atrazine + s-metolachlor	1737 + 1345	COC	Syngenta Crop Protection, LLC
Callisto Xtra	Atrazine + mesotrione	672 + 105	NIS	Syngenta Crop Protection, LLC
Degree Xtra	Acetochlor + atrazine	1512 + 751	-	Bayer CropScience
Lumaz EZ	Atrazine + s-metolachlor + mesotrione	524 + 1395 + 140	NIS	Syngenta Crop Protection, LLC
Coyote	*S*-metolachlor + mesotrione	1872 + 185	NIS	UPL NA Inc.

[1]Abbreviations: COC, Crop oil concentrate at 0.5% v/v; NIS, Non-ionic Surfactant at 0.25 v/v

Table 3.2. Averaged monthly air temperature and total cumulative precipitation at Kansas State University Agricultural Research Center in Hays, KS, during the 2023 and 2024 growing seasons.

	Average temperature		Total precipitation	
Months	2023	2024	2023	2024
	----------C----------		----------mm----------	
May	19	18	79	45
June	23	26	88	111
July	26	25	50	76
August	26	23	95	107
September	22	17	17	22
October	14	17	19	6

Table 3.3. Percent visual injury of pearl millet hybrids treated with various preemergence herbicides at 14, 28, and 56 days after application (DAA). [1, 2]

Herbicide	Rate	14 DAA			28 DAA			56 DAA		
		Hyb1	Hyb2	Hyb3	Hyb1	Hyb2	Hyb3	Hyb1	Hyb2	Hyb3
	g ha^{-1}	%								
Atrazine	2240	3 bA	4 cA	2 cA	2 bA	3 cA	3 cA	1 bA	2 cA	1 cA
S-metolachlor	1740	93 aA	90 aA	95 aA	95 aA	97 aA	97 aA	97 aA	97 aA	97 aA
Mesotrione	210	2 bA	2 cA	3 cA	3 bA	2 cA	2 cA	2 bA	2 cA	2 cA
Atrazine + s-metolachlor	1737 + 1345	97 aA	93 aA	97 aA	97 aA	97 aA	98 aA	97 aA	98 aA	98 aA
Atrazine + mesotrione	672 + 105	2 bA	3 cA	2 cA	4 bA	4 cA	3 cA	1 bA	1 cA	1 cA
Acetochlor + atrazine	1512 + 751	96 aA	72 bB	63 bC	96 aA	67 bB	50 bC	92 aA	43 bB	33 bB
Atrazine + s-metolachlor + Mesotrione	524 + 1395 + 140	93 aA	97 aA	93 aA	97 aA	96 aA	97 aA	98 aA	98 aA	97 aA
S-metolachlor + mesotrione	1872 + 185	93 aA	90 aA	91 aA	98 aA	97 aA	97 aA	98 aA	98 aA	98 aA

[1]Abbreviations: Hyb1, Hyb2, and Hyb3 were tested pearl millet hybrids

[2] Means followed by the same small alphabets within each column indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$); however, means followed by the same capital alphabets within each row indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$)

Table 3.4. Percent visual control of Palmer amaranth and green foxtail with preemergence herbicides at 14, 28, and 56 days after application (DAA) averaged across 3 pearl millet hybrids.[1]

Herbicide	Rate	Palmer amaranth			Green foxtail		
		14 DAA	28 DAA	56 DAA	14 DAA	28 DAA	56 DAA
	g ha^{-1}	% control					
Atrazine	2240	97 b	92 b	91 b	99 a	98 ab	97 b
S-metolachlor	1740	92 c	87 c	86 c	96 b	93 c	93 d
Mesotrione	210	99 a	98 a	97 a	100 a	100 a	98 ab
Atrazine + s-metolachlor	1737 + 1345	98 ab	95 ab	91 b	96 b	95 b	93 d
Atrazine + mesotrione	672 + 105	99 a	96 ab	95 ab	100 a	100 a	98 ab
Acetochlor + atrazine	1512 + 751	99 a	99 a	99 a	100 a	99 a	100 a
Atrazine + s-metolachlor + mesotrione	524 + 1395 + 140	98 ab	92 b	92 b	100 a	98 ab	97 b
S-metolachlor + mesotrione	1872 + 185	97 b	93 b	92 b	95 b	96 b	95 c

[1]Means followed by the same small alphabets within each column indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$).

Table 3.5. Palmer amaranth and green foxtail density and total weed biomass with PRE emergence herbicides at 28 and 56 days after application (DAA) averaged across 3 pearl millet hybrids at Kansas State University Agricultural Research Center in Hays, KS.[1]

Herbicide	Rate	Palmer amaranth	Green foxtail	Total weed biomass	Palmer amaranth	Green foxtail	Total weed biomass
		28 DAA			56 DAA		
	g ha^{-1}	——plants m^{-2}——		g m^{-2}	——plants m^{-2}——		g m^{-2}
Atrazine	2240	5 bc	1 c	10 cd	5 b	2 cd	20 bc
S-metolachlor	1740	7 b	3 b	24 b	4 bc	3 c	24 b
Mesotrione	210	1 e	0 cd	2 e	1 e	2 cd	20 bc
Atrazine + *S*-metolachlor	1737 + 1345	5 bc	2 bc	14 c	4 bc	3 c	20 bc
Atrazine + mesotrione	672 + 105	2 e	0 cd	6 de	3 cd	2 cd	16 c
Acetochlor + atrazine	1512 + 751	1 e	1 c	2 e	3 cd	0 d	24 b
Atrazine + *S*-metolachlor + mesotrione	524 + 1395 + 140	3 de	0 cd	12 cd	3 cd	1 d	14 c
S-metolachlor + mesotrione	1872 + 185	4 cd	4 b	14 c	2 de	5 b	14 c
Nontreated	-	14 a	7 a	49 a	15 a	10 a	82 a

[1] Means followed by the same small alphabets within each column indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$).

Table 3.6. Grain yield of pearl millet hybrids under various preemergence herbicides averaged across two growing seasons at Kansas State University Agricultural Research Center in Hays, KS.[1, 2]

Herbicide	Rate	Hyb1		Hyb2		Hyb3	
	g ha^{-1}	———		kg ha^{-1}		———	
Atrazine	2240	4,370	bA	4,484	bA	4,687	cA
S-metolachlor	1740	187	eA	106	dA	123	eA
Mesotrione	210	5,047	aA	5,250	aA	5,153	bA
Atrazine + s-metolachlor	1737 + 1345	170	eA	150	dA	180	eA
Atrazine + mesotrione	672 + 105	5,254	aB	5,674	aA	5,873	aA
Acetochlor + atrazine	1512 + 751	1,526	dB	3,205	cA	3,829	dA
Atrazine + s-metolachlor + mesotrione	524 + 1395 + 140	170	eA	296	dA	156	eA
S-metolachlor + Mesotrione	1872 + 185	124	eA	145	dA	151	eA
Nontreated	-	3,568	cA	3,415	cA	3,654	dA

[1]Abbreviations: Hyb1, Hyb2, and Hyb3 were tested pearl millet hybrids

[2] Means followed by the same small alphabets within each hybrid indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$), whereas means followed by the same capital alphabets within each herbicide treatment indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.0$)

Chapter 4 - Postemergence Herbicides for Crop Safety and Weed Control in Pearl Millet [*Pennisetum glaucum* (L.) R. Br.] Hybrids

4.1. Abstract

Lack of effective postemergence (POST) herbicides for weed control is a significant challenge in pearl millet. Greenhouse and field experiments were conducted in 2023 and 2024 at Kansas State University, Agricultural Research Center, Hays, Kansas to test various POST herbicides for crop safety and weed control in pearl millet. POST herbicides were evaluated on five pearl millet hybrids (Hyb1 to Hyb5) in the greenhouse and three hybrids (Hyb1, Hyb2, and Hyb3) in two separate field experiments (site 1 and 2) . Results indicated that all tested herbicides were safe on all pearl millet hybrids in the greenhouse (1 to 5% injury at 28 days after application, DAA) and both field experiments (1 to 4% injury), except imazamox and nicosulfuron (22 to 35 % injury). At field site 1, POST applied 2,4-D, dicamba, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, and dicamba + 2,4-D effectively controlled Palmer amaranth (88 to 91%) and reduced density (2 to 4 plants m-2) at 42 DAA. The least control (60 to 65%) and higher density (8 plants m-2) of Palmer amaranth was observed with imazamox and nicosulfuron. In contrast, imazamox and nicosulfuron effectively controlled (91 to 92%) and reduced density (2 plants m^{-2}) of green foxtail 42 DAA. No weed emergence was observed at field site 2. Across both field sites, a premix of 2,4-D + bromoxynil + fluroxypyr resulted in the highest grain yield of Hyb1 (3,866 to 4,619 kg ha^{-1}), Hyb2 (2,222 to 3,699 kg ha^{-1}), and Hyb3 (822 to 1,315 kg ha^{-1}) among all tested POST herbicides. These results highlight that POST herbicides tested in this study can be safely used for weed control in pearl millet.

Nomenclature: Acetochlor; atrazine; bromoxynil; 2,4-D; dicamba; fluroxypyr; imazamox; nicosulfuron; pyasulfotole; foxtail, *Setaria viridis* (L.) Beauv.; Palmer amaranth, *Amaranthus palmeri* S. Watson; Pearl millet, *Pennisetum glaucum* (L.) R. Br.

Keywords: Crop tolerance to herbicides; Weed management

4.2. Introduction

Pearl millet is a dryland cereal crop grown worldwide for food, feed, and nutritional values (Perumal et al. 2024). It is one of the most climate-resilient cereals that can tolerate high temperatures during the reproductive growth stage (Prasad et al. 2017). For instance, pearl millet can flower in high temperatures (>42 ºC) without affecting yield quantity and quality (Daduwal et al. 2024). Furthermore, pearl millet is a C_4 species with Kranz anatomy that enables it to efficiently fix carbon dioxide and use water (Howarth et al. 1996; Walsh and Lundgren 2024). In addition, pearl millet can grow and thrive well in soils with high salinity or soils with low water-holding capacities (Prasad et al. 2022). Pearl millet gains more importance and has been recognized as a nutri cereal due to its nutritional properties with potential in overcoming malnutrition and nutritional security (Rai et al. 2012; Satyavathi et al. 2021). Pearl millet is a significant source of energy (361 kcal per 100g) with the lowest glycemic index (55), and the highest fiber concentration (1.2g per 100g) compared to other major cereals (Nibhoria et al. 2024). Forage pearl millet has the highest crude protein content (12 to 14%) and low fiber content (2.8 to 17.6%) than corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench). Pearl millet with brown midrib is low in lignin, which improves forage digestibility (Bhattarai et al. 2019; Uppal et al. 2015).

Globally, pearl millet is the sixth most important cereal crop after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), corn, barley (*Hordeum vulgare* L.), and sorghum (Satyavathi et al. 2021). It is a staple food for >90 million people in the arid and semiarid regions of Africa and Asia with potential of ensuring global food needs (Satyavathi et al. 2024). Pearl millet production in 2024 was >30 million tons (MT) with India producing 13 MT that contribute 43% of the global production (USDA 2024). In the United States, pearl millet is mainly grown for livestock grazing, silage preparation, hay production over 0.6 million hectares (Myers 2002). It is mainly grown for food and forage; it also serves as a major component of poultry diet as well as livestock feed due to the absence of prussic acid (Yadav et al. 2024). Pearl millet can potentially be grown as an alternative crop for grain, forage, and/or cover crop (replacing fallow periods) in the dryland Central Great Plains (CGP) region in the existing cropping system (Kumar et al. 2024; Serba et al. 2020). However, improved agronomic practices for pearl millet production are warranted for widespread adoption of this alternative crop in these regions.

Among various biotic stresses, weeds are major constraints to the successful production of pearl millet (Kumar et al. 2024). Weeds compete for nutrients, water, sunlight, and space that ultimately reduce grain yields and increase production cost (Kaur et al. 2018). Due to its slow initial growth, pearl millet is a poor competitor with weeds in early growing stages (Balyan et al. 1993). The critical period of weed control for pearl millet ranges from 15 to 30 days after planting; therefore, early-season weed control is crucial to prevent any significant grain yield loss (Kumar et al. 2024). Depending upon growing conditions, season-long weed interference can reduce pearl millet grain yields by 5 to 94% (Balyan et al. 1993; Banga et al. 2000; Chaudhary et al. 2018; Das and Yaduraju 1995; Sharma and Jain 2003).

Producers primarily rely on herbicides for weed control in no-till dryland CGP region. However, limited preemergence (PRE) and postemergence (POST) herbicide options are currently labelled for use in pearl millet. Previous studies have reported the effectiveness of POST applied atrazine, 2,4-D, tembotrione and imazathapyr for weed control in pearl millet. For instance, effective control of broadleaf weeds has been reported with early POST application of atrazine (100 to 400 g ha^{-1}) or 2,4-D (500 to 700 g ha^{-1}) in pearl millet (Dowler et al. 1995; Girase et al. 2017; Samota et al. 2022; Singh et al. 2010). Similarly, Chaudhary et al. (2022) reported significant reductions in weed density and total weed dry weights with a single POST application of tembotrione (80 to 100 g ha^{-1}). In contrast, Singh et al. (2016) reported significant phytotoxic injury and grain yield loss in pearl millet with a POST application of imazethapyr (40 g ha^{-1}). Nonetheless, limited information exists on the crop safety and effectiveness of various POST herbicides for broad-spectrum weed control (both grass and broadleaf) in pearl millet in the CGP region. In addition, the widespread evolution of herbicide-resistant weeds is serious challenge in the CGP region and warrants the need for effective chemical-based weed control programs in pearl millet (Heap 2025; Kumar et al. 2024). To fill these knowledge gaps, greenhouse and field studies were initiated to investigate the effectiveness of various POST herbicides (labeled in sorghum) for crop safety and broad-spectrum weed control in advanced pearl millet hybrids developed at Kansas State University. We hypothesized that pearl millet may have natural tolerance to POST herbicides labeled in sorghum, as sorghum and pearl millet belong to the same family, Poaceae'. The main objectives for this research were to 1) investigate the safety of newly developed pearl millet hybrids to POST herbicides, 2) determine the effectiveness of POST herbicides for weed control in pearl millet, and 3) determine the impact of POST herbicides on grain yields.

4.3. Material and Methods

4.3.1. Greenhouse Experiment

The advanced pearl millet parental lines initially developed at Kansas State University, Agricultural Research Center, Hays, Kansas (KSU-ARCH) (Ramalingam et al. 2024; Serba et al. 2017) were used to develop pearl millet hybrids in summer of 2022. Selected five pearl millet hybrids (Hyb1: ARCH-27A/ARCH-65R; Hyb2: ARCH-37A/ARCH-49R; Hyb3: ARCH-41A/ARCH-70R; Hyb4: ARCH-30A/ARCH-62R; Hyb5: ARCH-32A/ARCH-21R) were used in this study. Greenhouse studies were conducted in the summer of 2023 and repeated in the fall of 2023 at KSU-ARCH. Seeds of each selected pearl millet hybrid were separately planted in 10 cm size squared plastic pots filled with commercial potting mixture (Miracle-Gro Moisture Control Potting Mix, Miracle-Gro Lawn Products, Marysville, OH). Experiments were conducted in a randomized complete block (blocked by herbicides) design with 12 replications (1 pot = 1 plant = 1 rep). The greenhouse conditions were maintained at 32/29 ± 5 C day/night temperatures with a 15/9 h photoperiod and plants were watered daily. Total eight POST herbicides, including acetochlor + atrazine, atrazine, bromoxynil, bromoxynil + pyrasulfotole, 2,4-D, 2,4-D + bromoxynil + fluroxypyr, dicamba, and dicamba + 2,4-D were tested on all five hybrids at the seedling stage (3 to 4 leaf stage and 10- to 12-cm tall plants). A nontreated weedy check treatment was also included for comparisons. A cabinet spray chamber equipped with an even flat-fan nozzle tip (Tee Jet XR8001E, Spraying System) calibrated to deliver 141 L ha^{-1} of the spray solution at 240 kpa was used. After application of POST herbicides, plants were returned back to the greenhouse and were watered after 24 hours.

4.3.2. Field Experiment

Field experiments were conducted at two different sites in summer 2024 at KSU-ARCH. The soil type at the study sites (site 1 = 38.86202°N, 99.33488°W and site 2 = 38.85144°N, 99.34108°W) was Roxbury silt loam, with a pH of 6.9 and 7.1 and organic matter of 1.5% and 1.7%, respectively. Field site 1 was historically under a conventionally tilled sorghum-fallow rotation for >5 years, whereas site 2 was under no-till wheat-sorghum-fallow rotation for >10 years. Two pearl millet hybrids (Hyb1: ARCH37A/ARCH49R; Hyb2: ARCH32A/ARCH73R) developed by millet breeding program at KSU-ARCH, along with one commercial hybrid (Hyb3: Tif leaf) were used for field studies in both sites. Total ten POST herbicides at labelled field-use rates in sorghum were used (Table 1). A nontreated weedy check was included for comparison of treatments. A burndown treatment of glyphosate (1260 g ha^{-1}) was used to kill all weeds present at site 2 prior to planting. At both field sites, each hybrid was planted at a density of 172,149 seeds ha^{-1} in rows spaced 76 cm apart on June 16, 2024. All selected POST herbicides were applied 21 days after planting (4- to 5-leaf stage and 12 to 15 cm tall) using a CO_2-operated backpack sprayer equipped with flat-fan 110015XR nozzles (TeeJet Technologies, Glendale Heights, IL) calibrated to deliver spray solution at the rate of 140 L ha^{-1} at consistent pressure of 276 kPa. A supplemental irrigation of 2.5 cm was applied using a sprinkler irrigation system on June 17, 2024 at field site 1, and no supplemental irrigation was given at field site 2. Experiments were conducted in a split-plot (hybrids as main plots and POST herbicides as a sub-plots) randomized complete block design with 3 replications (each plot 1.5 m wide and 3 m long with two rows of pearl millet). All standard agronomic practices on pearl millet production, including time of planting, seeding rate, nutrient and other management practices were followed as recommended. Data on mean monthly air temperature and total monthly precipitation during

the field experiments were also recorded from the K-State Mesonet weather station (https://mesonet.k-state.edu/) and summarized in Table 2.

4.3.3. Data Collection

In greenhouse experiments, data on percent visual injury were recorded at 7, 14, and 28 DAA of POST herbicides on a scale of 0 to 100% (where 0% = no injury and 100% = complete death). Injury symptoms included stunting, chlorosis, and necrosis of treated plants for each hybrid. At 28 DAA, the aboveground shoot biomass of treated plants was collected by cutting plants from the soil surface and dried at 65 C for five days to determine the shoot dry biomass reduction (% of nontreated). In field studies at both sites, data on percent visual injury on a scale of 0 to 100% (where 0% = no injury and 100% = complete death) was recorded at 14 and 28 DAA. Percent visual control ratings of Palmer amaranth and green foxtails were recorded at 28 and 42 DAA at field site 1, whereas no weed emergence was observed at field site 2. The density of individual weed species was also recorded at 42 DAA using 1-m^2 quadrat from the center of each plot at site 1. At maturity, plants were manually harvested using two 1 m rows from each plot to estimate the grain yield. Harvested plants were dried in an oven at 65 °C for 7 days, and grain heads were threshed using a millet thresher (BT-14 Single Plant Belt Thresher, ALMACO, Nevada, IA) and weighed to estimate the grain yield (kg ha^{-1}) of each pearl millet hybrid under each POST herbicide tested.

4.3.4. Statistical Analyses

Treatment-by-experimental run interaction was nonsignificant for greenhouse experiments (P = 0.463); therefore data (visual crop injury and shoot dry biomass reduction) were pooled across

experimental runs. For field experiments, data were analyzed and presented separately for each site to account for differences in environmental conditions and agronomic practices (field site 1 was under sprinkler irrigation, whereas field site 2 was under dryland). Data were tested for homogeneity of variance and normality of the residuals using the PROC UNIVARIATE procedure in SAS 9.3 (SAS Institute, Inc., SAS Campus Drive, Cary, NC), and all data met these assumptions. The fixed effects in the ANOVA for greenhouse experiments included POST herbicides, pearl millet hybrids, and their interactions. The fixed effects in the ANOVA for the field study included POST herbicides, pearl millet hybrids, and their interactions. The random effects in the ANOVA included replication and all interactions involving replication for both greenhouse and field experiments. Data from nontreated plots were excluded from the analyses. The treatment means were separated using Fisher's Protected least significant difference test ($P < 0.05$).

4.4. Results and Discussion

4.4.1. Greenhouse Study

4.4.1.1. Percent visual injury

An interaction between pearl millet hybrids and POST herbicides was nonsignificant ($P = 0.821$) for percent visual injury; however, the main effect of POST herbicides was significant ($P < 0.0001$). Averaged across all hybrids, the highest injury (17%) was observed with POST applied acetochlor + atrazine at 14 DAA followed by 15% injury with bromoxynil alone, bromoxynil + pyrasulfotole and dicamba + 2,4-D (Table 3). Other tested POST herbicides, including atrazine, 2,4-D, dicamba, and 2,4-D + bromoxynil + fluroxypyr relatively had lower injury (12 to 13%) at 14 DAA. In contrast, only 1 to 3% injury was observed with majority of POST herbicides tested

at 28 DAA. POST applied acetochlor + atrazine resulted in 5% averaged injury across five pearl millet hybrids at 28 DAA (Table 3).

4.4.1.2. Shoot dry biomass reduction

Consistent with visual injury, only the main effect of POST herbicides was significant ($P < 0.0001$) for the shoot dry biomass reduction (% of nontreated). Averaged across hybrids, all POST herbicides reduced shoot dry biomass as compared to nontreated weedy check. For instance, POST applied acetochlor + atrazine resulted in the highest shoot dry biomass reduction (9%) (Table 3). Furthermore, the shoot dry biomass reduction was 6 to 7% with POST applied bromoxynil, bromoxynil + pyrasulfotole, and dicamba + 2,4-D (Table 3). In contrast, POST applied atrazine, 2,4-D, dicamba, and 2,4-D + bromoxynil + fluroxypyr resulted in the least shoot dry biomass reduction (2 to 4%) at 28 DAA (Table 3).

4.4.2. Field Experiments

The total monthly precipitation during the experimental period in the 2024 growing season ranged from 6 to 111 mm, whereas the mean monthly air temperature during the experimental period ranged from 17 to 26 °C (Table 2). These weather conditions represent a typical growing season in semi-arid western Kansas.

4.4.2.1. Pearl millet injury

Field site 1

The main effect of POST herbicides was significant ($P < 0.0001$) for pearl millet injury. Averaged across pearl millet hybrids, POST applied atrazine, acetochlor + atrazine, 2,4-D, 2,4-D + bromoxynil + fluroxypyr, bromoxynil, bromoxynil + pyrasulfotole, dicamba, and dicamba +

2,4-D resulted in 1 to 3% visual injury at 28 DAA, except for imazamox and nicosulfuron (Table 4). In contrast, POST applied imazamox and nicosulfuron resulted in visual injury of 22 to 27% averaged across five hybrids at 28 DAA (Table 4). These results are consistent with Tugoo et al. (2025), who have recently reported a variable injury (5 to 70%) among 56 different pearl millet parental lines with POST applied imazamox and nicosulfuron.

Field site 2

Averaged across pearl millet hybrids, POST applied atrazine, acetochlor + atrazine, 2,4-D, 2,4-D + bromoxynil + fluroxypyr, bromoxynil, bromoxynil + pyrasulfotole, dicamba, and dicamba + 2,4-D resulted in 1 to 4% visual injury at 28 DAA, which was slightly higher than field site 1 (Table 5). Furthermore, POST applied imazamox and nicosulfuron resulted in visual injury of 29 to 35% at 28 DAA (Table 5). Similar results of visual injury with imazamox and nicosulfuron ranging from 5 to 70% were reported by Tugoo et al. (2025).

4.4.2.2. Palmer amaranth control and density

Field site 1

The main effect of POST herbicides was significant ($P < 0.0001$) for Palmer amaranth control at 28 and 42 DAA and density at 42 DAA. Averaged across three pearl millet hybrids, POST applications of 2,4-D, dicamba, dicamba + 2,4-D, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr provided effective control (91 to 96%) of Palmer amaranth at 28 DAA (Table 4). These results are consistent with Jhala et al. (2014), who previously reported 94 to 98% control of Palmer amaranth with 2,4-D and dicamba in a greenhouse study in Nebraska. Similarly, Aulakh et al. (2021) reported 88 to 92% control of glyphosate-resistant (GR) Palmer

amaranth with POST applied 2,4-D and dicamba in a greenhouse study in Connecticut. In contrast, Kumar et al. (2021a) previously reported slightly lower control of Palmer amaranth with POST applied dicamba (79% control), 2,4-D (83% control), dicamba + 2,4-D (86% control), and 2,4-D + bromoxynil + fluroxypyr (72% control) in wheat stubble. In that study, it is important to note that POST herbicides were applied at taller Palmer amaranth (at panicle initiation stage) in wheat stubble (Kumar et al. 2021a). In current study, control with POST applied atrazine, bromoxynil, and acetochlor + atrazine averaged 82 to 85% at 28 DAA (Table 4). These results are contrary to Chahal et al. (2017), who previously reported lower control of GR Palmer amaranth with POST applied atrazine (23% control) and bromoxynil (9% control) in a greenhouse study. In that study, it is important to note the tested GR Palmer amaranth population was also suspected of resistance to photosystem (PS II) inhibiting herbicides (Chahal et al. 2017), whereas, the herbicide resistance status of Palmer amaranth population in current study was not known. Among all POST herbicides tested, the least control of Palmer amaranth was observed with imazamox and nicosulfuron ranging from 70 to 75% at 28 DAA (Table 4). These results are consistent with Chahal et al. (2017), who previously reported lower control (23%) of GR Palmer amaranth with POST applied imazamox in a greenhouse study. At 42 DAA, Palmer amaranth control declined slightly with majority of the POST herbicides; however, the trend remained similar to what was observed at 28 DAA. For instance, POST applied 2,4-D, dicamba, dicamba + 2,4-D, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr provided excellent control (88 to 91%) of Palmer amaranth at 42 DAA. Control with POST applied atrazine, bromoxynil, acetochlor + atrazine averaged 78% at 42 DAA, whereas, the control declined to 60 to 65% with nicosulfuron and imazamox (Table 4). Lower control of Palmer amaranth with imazamox and nicosulfuron was probably due to widespread presence of

resistance to ALS inhibiting herbicides among Palmer amaranth populations in the CGP region (Heap 2025).

Consistent with percent visual control, all POST herbicides also reduced the density of Palmer amaranth at 42 DAA. For instance, POST applied 2,4-D, dicamba, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, dicamba + 2,4-D, and acetochlor + atrazine significantly reduced Palmer amaranth density (2 to 5 plants m^{-2}) as compared to nontreated plots (18 plants m^{-2}) at 42 DAA (Table 4). Furthermore, POST applied atrazine, bromoxynil, imazamox, and nicosulfuron also significantly reduced Palmer amaranth density (6 to 8 plants m^{-2}) as compared to nontreated plots (18 plants m^{-2}) at 42 DAA (Table 4).

4.4.2.3. Green foxtail control and density

The main effect of POST herbicides was significant ($P < 0.0001$) for green foxtail control at 28 and 42 DAA and density at 42 DAA. Averaged across three pearl millet hybrids, POST applied imazamox and nicosulfuron provided the highest control (91 to 94%) of green foxtail at 28 and 42 DAA (Table 4). Kumar et al. (2021b) have previously reported 77 to 83% control of green foxtail with POST applied imazamox and nicosulfuron in a fallow study. In current study, control with POST applied bromoxynil alone, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr averaged 84% at 28 DAA, which further declined to 78% averaged at 42 DAA (Table 4). POST applied atrazine alone or acetochlor + atrazine provided 70 to 75% control at 28 DAA and 63 to 68% control at 42 DAA. As expected, the least control (10 to 15%) of green foxtails was observed with 2,4-D or dicamba applied alone at 28 and 42 DAA (Table 4).

Consistent with visual control, POST applied imazamox and nicosulfuron significantly reduced green foxtail density (2 plants m^{-2}) as compared to nontreated plots (12 plants m^{-2}) at 42

DAA. Similarly, a significant reduction in green foxtail density (4 to 5 plants m^{-2}) was observed with POST applied atrazine, bromoxynil, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, and acetochlor + atrazine when compared with nontreated plots (12 plants m^{-2}) (Table 4). The least reduction in green foxtail density (averaged 10 plants m^{-2}) was observed with POST applied 2,4-D, dicamba, or dicamba + 2,4-D at 42 DAA (Table 4).

Field site 2

No weed emergence was observed at field site 2; therefore, no weed control data were collected from this site. Differences in tillage practices and supplemental irrigation between experimental sites (site 1 was irrigated and tilled while site 2 was under no-tilled dryland) were probably the reasons for the significant differences.

4.4.2.4. Pearl millet grain yield

Field site 1

Among three pearl millet hybrids tested, the Hyb1 outperformed than other two hybrids (Hyb2 & Hyb3) and produced the highest grain yield across all tested herbicides. For instance, minimum crop injury and effective weed control achieved with POST application of dicamba alone or 2,4-D + bromoxynil + fluroxypyr resulted in the highest grain yields (4,236 to 4619 kg ha^{-1}) of Hyb1 (Table 6). Furthermore, the grain yield of Hyb1 ranged from 3,584 to 4,044 kg ha^{-1} with POST applied 2,4-D, atrazine, bromoxynil + pyrasulfotole, dicamba + 2,4-D, and acetochlor + atrazine. The grain yield of Hyb1 with POST applied bromoxynil alone was 3,483 kg ha^{-1}, which did not differ from the nontreated weedy check (3,359 kg ha^{-1}). The least grain yield (1,040 to 1,486 kg ha^{-1}) of Hyb1 was observed with imazamox and nicosulfuron (Table 6).

Consistent with visual injury and weed control, the majority of the POST herbicides (including nontreated) resulted in grain yield in the range of 3,008 to 3,699 kg ha^{-1} for Hyb2, except imazamox (970 kg ha^{-1}) and nicosulfuron (1,289 kg ha^{-1}) (Table 5). High visual crop injury and relatively lesser weed control resulted in lower grain yield for Hyb2 with POST applied imazamox and nicosulfuron. The highest grain yield of Hyb2 was observed with 2,4-D + bromoxynil + fluroxypyr (3,699 kg ha^{-1}), which did not differ from bromoxynil + pyrasulfotole (3,374 kg ha^{-1}) and dicamba + 2,4-D (3,559 kg ha^{-1}). A similar grain yield trend was also observed for Hyb3; however, the overall grain yield of Hyb3 was significantly lesser compared to Hyb1 and Hyb2. The majority of the POST herbicides (including nontreated) resulted in a grain yield of Hyb3 in the range of 1,078 to 1,475 kg ha^{-1}, except for imazamox (560 kg ha^{-1}) and nicosulfuron (435 kg ha^{-1}) (Table 6).

Field site 2

Overall, the grain yield of all three hybrids at field site 2 was lower compared to field site 1 (Table 6). The grain yield of Hyb1 and Hyb2 in nontreated weedy check was 1,833 kg ha^{-1} and 1,265 kg ha^{-1}, respectively. The highest grain yield (3,866 kg ha^{-1}) of Hyb1 was observed with POST applied 2,4-D + bromoxynil + fluroxypyr followed by bromoxynil alone (3,096 kg ha^{-1}) and dicamba + 2,4-D (3,303 kg ha^{-1}) (Table 6). Furthermore, grain yield of Hyb1 with 2,4-D, dicamba, atrazine, bromoxynil + pyrasulfotole, and acetochlor + atrazine ranged from 2,130 kg ha^{-1} to 2,500 kg ha^{-1}. Similar to site 1, the lowest grain yield of Hyb1 was observed with imazamox (1,202 kg ha^{-1}) and nicosulfuron (728 kg ha^{-1}) (Table 6).

For Hyb2, the highest grain yield (2,199 kg ha^{-1}) was observed with POST applied dicamba, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr. Furthermore, POST

applied 2,4-D, atrazine, bromoxynil, dicamba + 2,4-D, and acetochlor + atrazine resulted in grain yield of Hyb2 in the range of 1,395 to 1,728 kg ha^{-1}. Similar to other hybrids, the least grain yield (542 to 928 kg ha^{-1}) of Hyb2 was observed with POST applied imazamox and nicosulfuron (Table 6). Similar to site 1, the overall grain yield of Hyb 3 was lower for all tested POST herbicides. For instance, the highest grain yield (640 to 822 kg ha^{-1}) of Hyb3 was observed with POST applied bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, and dicamba + 2,4-D (Table 5). Grain yield of Hyb3 with rest of the POST herbicides (including nontreated) ranged from 142 to 604 kg ha^{-1}, with least grain yield observed for imazamox and nicosulfuron (Table 6).

4.5. Practical Implications

Results from greenhouse and field study indicated the majority of the POST herbicides tested were safer on pearl millet hybrids, except imazamox and nicosulfuron with significant visual injury (22 to 35%) across all three hybrids and two field sites. However, green foxtail control was excellent (90 to 92%) with POST-applied imazamox and nicosulfuron. Furthermore, POST applied 2,4-D + bromoxynil + fluroxypyr, bromoxynil + pyrasulfotole, and 2,4-D, dicamba or dicamba + 2,4-D were effective in controlling Palmer amaranth (>90% control). It is important to note that the POST herbicides assessed in this study are not yet approved for use on pearl millet. However, the information gained through this research could potentially support the registration process for these herbicides. Future research across various locations, considering diverse environmental and soil conditions, as well as testing commercial pearl millet hybrids (on-farm trials) will be crucial for advancing the registration of these herbicides for pearl millet. Future investigations are needed to evaluate combinations of PRE and POST herbicides (two-pass strategies) to ensure crop safety and effective season long weed control in pearl millet.

Studies should also explore combining both chemical and non-chemical methods of weed control for pearl millet.

Table 4.1. List of selected POST herbicides, their rates, and adjuvants tested on pearl millet hybrids at Kansas State University Agricultural Research Center in Hays, KS.

Trade name	Common name	Rates	Adjuvant[1]	Manufacturer
		g ae or ai ha^{-1}		
2,4-D Amine	2,4-D	532	-	Alligare, LLC
Clarity®	Dicamba	280	-	BASF Ag Products
Atrazine 4L	Atrazine	2240	-	Loveland Products, Inc.
Huskie®	Bromoxynil + pyrasulfotole	300 + 40	NIS	Bayer CropScience
Moxy® 2E	Bromoxynil	420	NIS	WinField United
Kochiavore®	2,4-D + bromoxynil + fluroxypyr	351+ 351+140	-	WinField United
Weedmaster	Dicamba + 2,4-D	140 + 402	-	Nufarm Americas, Inc.
Degree Xtra®	Acetochlor + atrazine	1513 + 751	-	Bayer CropScience
Beyond®	Imazamox	52	COC	BASF Ag Products
Zest™ WDG	Nicosulfuron	70	COC	Corteva Agriscience United States

[1]Abbreviations: COC, Crop oil concentrate at 0.5% v/v; NIS, Nonionic surfactant at 0.25 %v/v

Table 4.2. Average monthly air temperature and total cumulative precipitation at Kansas State University Agricultural Research Center near Hays, KS, during the 2023 and 2024 growing season.

Months	2024	2024
	----------°C---------	----------mm--------
May	18	45
June	26	111
July	25	76
August	23	107
September	17	22
October	17	6

Table 4.3. Effect of POST herbicides on visual injury (%) and shoot biomass reduction (% of nontreated) averaged across five pearl millet hybrids at 28 d after application (DAA) in greenhouse experiments at Kansas State University, Agricultural Research Center, Hays, Kansas[1]

Herbicide	Rate	14 DAA	28 DAA	28 DAA
	g ae or ai ha^{-1}	% injury		% of nontreated
2,4-D	532	12 d	2 c	4 c
Dicamba	280	12 d	2 c	3 c
Atrazine	2240	13 c	2 c	4 c
Bromoxynil + pyrasulfotole	300 + 40	15 b	3 b	7 b
Bromoxynil	420	15 b	3 b	6 b
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	13 c	1 d	2 c
Dicamba + 2,4-D	140 + 402	15 b	3 b	6 b
Acetochlor + atrazine	1513 + 751	17 a	5 a	9 a

[1]Means followed by the same small alphabets within each column indicate no statistical difference by the Fisher's protected LSD (least significant difference) test ($\alpha = 0.05$)

Table 4.4. Percent visual crop injury, Palmer amaranth and green foxtail control, and density with POST herbicides averaged across three pearl millet hybrids at experimental site 1 at Kansas State University, Agricultural Research Center, Hays, Kansas.[1]

Herbicide	Rate	Injury	Palmer amaranth			Green foxtails		
			28 DAA	42 DAA	42 DAA	28 DAA	42 DAA	42 DAA
	g ae or ai ha^{-1}	%	% control		Plants m^{-2}	% control		Plants m^{-2}
2,4-D	532	3 c	91 a	88 a	3 c	15 e	12 e	10 a
Dicamba	280	2 c	92 a	90 a	2 c	18 de	15 de	10 a
Atrazine	2240	2 c	82 b	77 b	6 b	70 c	63 c	6 b
Bromoxynil + pyrasulfotole	300 + 40	2 c	94 a	89 a	4 c	85 b	79 b	5 b
Bromoxynil	420	2 c	83 b	78 b	6 b	82 b	77 b	5 b
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	1 c	96 a	91 a	2 c	84 b	78 b	5 b
Dicamba + 2,4-D	140 + 402	2 c	95 a	91 a	3 c	23 d	18 d	10 a
Acetochlor + atrazine	1513 + 751	3 c	85 b	78 b	5 bc	75 c	68 c	6 b
Imazamox	52	22 b	75 c	65 c	8 b	94 a	92 a	2 c
Nicosulfuron	70	27 a	70 c	60 c	8 b	92 a	91 a	2 c
Nontreated	-	-	-	-	18 a	-	-	13 a

[1] Means followed by the same small alphabets within each column indicate no statistical difference by the Fisher's protected LSD (least significant difference) test ($\alpha = 0.05$)

Table 4.5. Percent visual crop injury at 14 and 28 DAA with POST herbicides averaged across three pearl millet hybrids at experimental site 2 at Kansas State University, Agricultural Research Center, Hays, Kansas.[1]

Herbicide	Rate	14 DAA		28 DAA	
	g ae or ai ha^{-1}	%		%	
2,4-D	532	5	cd	2	cd
Dicamba	280	4	d	2	cd
Atrazine	2240	5	cd	3	cd
Bromoxynil + pyrasulfotole	300 + 40	4	d	2	cd
Bromoxynil	420	4	d	2	cd
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	5	cd	2	cd
Dicamba + 2,4-D	140 + 402	4	d	1	d
Acetochlor + atrazine	1513 + 751	8	c	4	c
Imazamox	52	35	b	29	b
Nicosulfuron	70	40	a	35	a
Nontreated	-	-	-	-	-

[1] Means followed by the same small alphabets within each column indicate no statistical difference by the Fisher's protected LSD (least significant difference) test ($\alpha = 0.05$)

Table 4.6. Grain yield of three pearl millet hybrids as influenced by POST herbicides at two experimental sites at Kansas State University, Agricultural Research Center, Hays, Kansas.[1, 2]

Herbicide	Rate	Site 1						Site 2					
		Hyb1		Hyb2		Hyb3		Hyb1		Hyb2		Hyb3	
	g ae or ai ha^{-1}	kg ha^{-1}						kg ha^{-1}					
2,4-D	532	3,903	bA	3,094	bA	1,158	abB	2,371	cA	1,395	cB	604	bC
Dicamba	280	4,236	abA	3,008	bB	1,078	bC	2,130	cA	2,186	aA	451	cB
Atrazine	2240	3,662	bcA	3,145	bB	1,129	abC	2,495	cA	1,502	bcB	417	cC
Bromoxynil + pyrasulfotole	300 + 40	3,903	bA	3,374	abB	1,475	aB	2,500	cA	2,189	aA	744	aB
Bromoxynil	420	3,483	cA	3,173	bA	1,131	abB	3,096	bA	1,798	bB	373	cC
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	4,619	aA	3,699	aB	1,315	aC	3,866	aA	2,222	aB	822	aC
Dicamba + 2,4-D	140 + 402	4,044	bA	3,559	aB	1,295	aB	3,303	bA	1,853	bB	676	abC
Acetochlor + atrazine	1513 + 751	3,584	bcA	3,241	abA	1,057	bB	2,267	cA	1,761	bB	640	abC
Imazamox	52	1,486	dA	970	cAB	560	cB	1,202	dA	928	dA	382	cB
Nicosulfuron	70	1,040	dA	1,289	cA	435	cB	728	eA	542	eA	142	dB
Nontreated	-	3,359	cA	3,139	bA	1,079	bB	1,833	cdA	1,265	cdB	357	cC

[1]Abbreviations: Hyb1, Hyb2, and Hyb3 were tested pearl millet hybrids

[2]Means followed by the same small alphabets within each hybrid indicate no statistical difference by the Fisher's protected LSD (least significant difference) test ($\alpha = 0.05$), whereas means followed by the same capital alphabets within each herbicide treatment indicate no statistical difference by the Fisher's protected LSD test ($\alpha = 0.05$)

Chapter 5 - Conclusion and Future Research

Screening pearl millet parental lines provided significant insights into the herbicide sensitivity of these lines and pearl millet hybrids tolerance to various PRE and POST herbicides. Notably, a single dose bioassay of 56 pearl millet parental lines confirmed the reduced sensitivity of pearl millet to imazamox and nicosulfuron. Dose-response studies further revealed a moderate level of tolerance to imazamox (3.2- to 12.2-fold) and nicosulfuron (1.5- to 6.0-fold) in selected pearl millet lines compared to selected sensitive pearl millet lines. Thus, reduced sensitivity to imazamox and nicosulfuron was observed in advanced pearl millet parental lines, marking the first known report of natural variation for herbicide tolerance in pearl millet. These findings are critical for the development of pearl millet hybrids that are tolerant to ALS-inhibiting herbicides, which could provide producers with more effective weed control options, particularly for grass weed control. Such hybrids could greatly enhance weed management and contribute to the broader adoption of pearl millet in the central Great Plains drylands, benefiting both grain and forage production systems. The breeding efforts at KSU-ARCH, KS, focusing on creating high-yielding hybrids with ALS herbicide tolerance, represent a significant step forward in this area. However, the underlying mechanisms conferring reduced sensitivity to imazamox and nicosulfuron in pearl millet need to be identified. This could involve studies on molecular genetics, enzyme activity, and herbicide metabolism pathways.

Additionally, field studies evaluate the effectiveness of various PRE and POST herbicide for crop safety and weed control in pearl millet hybrids. Results from PRE herbicide evaluations indicated that atrazine, mesotrione, and their combinations were effective for controlling Palmer amaranth and green foxtail without significant injury to pearl millet hybrids. However, certain combinations of *S*-metolachlor with other herbicides caused substantial injury to the hybrids,

highlighting the need for hybrid-specific herbicide recommendations. Although PRE herbicides such as acetochlor + atrazine were effective in controlling weeds, differential responses were observed across all selected hybrids for crop safety. This study lays the groundwork for further research into the safety and effectiveness of these herbicides in pearl millet and could support future herbicide registrations for the crop.

For POST herbicide evaluations, several herbicides, including 2,4-D + bromoxynil + fluroxypyr and bromoxynil + pyrasulfotole, were safe on the hybrids and provided excellent control of broadleaf weeds such as Palmer amaranth. However, imazamox and nicosulfuron resulted in significant injury across all hybrids. While these herbicides were effective in controlling green foxtail, further research is needed to optimize POST herbicide options that are safer for pearl millet and effective in controlling weeds. Furthermore, the development of integrated weed management strategies, combining both chemical and non-chemical methods, should be explored. Additionally, further studies are needed to investigate effective combinations of PRE and POST herbicides to ensure season-long weed control while maintaining crop safety. Given the variability in herbicide response, future research should involve field trials across diverse environmental and soil conditions. These studies, including trials with commercial hybrids, will provide a broader understanding of herbicide performance and safety under real farm conditions.

Chapter 6 - References

Abit MJ, Al-Khatib K (2013) Metabolism of quizalofop and rimsulfuron in herbicide resistant grain sorghum. Pest Biochem Physiol 105(1):24–7

Anonymous (2021) Select Max® herbicide label. San Ramon, CA: Valent U.S.A. LLC. https://s3-us-west-1.amazonaws.com/agrian-cg-fs1 production/pdfs/Select_Maxr1i_Herbicide_with_Inside_Technologytm_Label.pdf. Accessed: November 1, 2024

Ahmed K, Shoaib M, Akhtar MN, Iqbal Z (2014) Chemical analysis of different cereals to access nutritional components vital for human health. Int J Chem Biochem Sci 6:61–67

Armel GR, Wilson HP, Richardson RJ, Hines TE (2003) Mesotrione, acetochlor, and atrazine for weed management in corn (*Zea mays*). Weed Technol 17(2):284–290

Aulakh JS, Chahal PS, Kumar V, Price AJ, Guillard K (2021) Multiple herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Connecticut: confirmation and response to POST herbicides. Weed Technol 35(3):457–463

Awadelkareem AM, Hassan EG, Fageer ASM, Sulieman AME, Mustafa AMI (2015) Nutritive value of two sorghum cultivars. Int J Food Nutr Sci 4:1–7

Bajwa AA, Mahajan G, Chauhan BS (2015) Nonconventional weed management strategies for modern agriculture. Weed Sci 63:723–747

Balyan RS, Kumar S, Malik RK, Panwar RS (1993) Post-emergence efficacy of atrazine in controlling weeds in pearl millet. Indian J Weed Sci 25:7–11

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

Banks S, Stewart T (1998) Factsheet: forage pearl millet. Ontario Ministry of Agriculture, Food, and Rural Affairs. Publication #98–045

Barbieri GF, Young BG, Dayan FE, Streibig JC, Takano H, Merotto A Jr, Avila LA (2022) Herbicide mixtures: interactions and modeling. Adv Weed Sci 40:e020220051

Bhattarai B, Singh S, West CP, Saini R (2019) Forage potential of pearl millet and forage sorghum alternatives to corn under the water-limiting conditions of the Texas high plains: A review. Crop Forage Turfgrass Manage 5:1–2

Bollam S, Mahendrakar M, Marla S, Kanuganahalli V, Addanki KR, Srivastava RK (2024) Genetic and Genomic Approaches for Accelerated Pearl Millet Breeding. In: Pearl Millet: A Resilient Cereal Crop for Food, Nutrition, and Climate Security. Springer Nature Singapore, pp 81–120

Brookes G (2014) Weed control changes and genetically modified herbicide-tolerant crops in the USA 1996–2012. GM Crops Food 5:321–332

Buhler BD (1991) Early preplant atrazine and metolachlor in conservation tillage corn (*Zea mays*). Weed Technol 5(1): 66–71

Chaudhary C, Dahiya S, Rani S, Pandey S (2018) Review and outlook of weed management in Pearl millet. Int J Crop Sci 6:2346–2350

Chahal PS, Varanasi VK, Jugulam M, Jhala AJ (2017) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska: Confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. Weed Technol 31(1):80–93

Cherney JH, Axtell JD, Hassen MM, Anliker KS (1988) Forage quality characterization of a chemically induced brown-midrib mutant in pearl millet. Crop Sci 28:783-787

Cook BG, BC Pengelly, SD Brown, JL Donnelly, DA Eagles, MA Franco, J Hanson, BF Mullen, IJ Partridge, M Peters, R Schultze-Kraft (2005). Tropical Forages: an interactive selection

tool. Web Tool. CSIRO, DPI&F(Qld), CIAT and ILRI, Brisbane, Australia. Available at https://hdl.handle.net/10568/49072

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

Currie R, Geier P (2016) Preemergence weed control with FulTime NXT and competitive standards in grain sorghum, Kansas Agricultural Experiment Station Research Reports. Available at https://doi.org/10.4148/2378-5977.1273 Accessed: January 25, 2025

Daduwal HS, Bhardwaj R, Srivastava RK (2024) Pearl millet a promising fodder crop for changing climate: A review. Theor Appl Genet 137:169

Das TK, Yaduraju NT (1995) Crop weed competition studies in some kharif crops: 11, nutrient uptake and yield reduction. Ann Plant Sci 3(2): 95–99

Dayakar Rao B, Bhaskarachary K, Arlene Christina GD, Sudha Devi G, Vilas AT, Tonapi A (2017) Nutritional and health benefits of millets. ICAR Indian Institute of Millets Research, Rajendranagar, Hyderabad, pp 2.

Deevi KC, Swamikannu N, Pingali PR, Gumma MK (2024) Current Trends and Future Prospects in Global Production, Utilization, and Trade of Pearl Millet. In: Pearl Millet in the 21st Century: Food-Nutrition-Climate Resilience-Improved Livelihoods. Springer Nature Singapore, pp 1–33

Degenhart NR, Werner BK, Burton GW (1995) Forage yield and quality of a brown mid-rib mutant in pearl millet. Crop Sci 35:986–988

Diatta AA (2016) Effects of biochar application on soil fertility and pearl millet (*Pennisetum glaucum* L.) yield. Ph. D. dissertation. Blacksberg, Virginia Tech. Available at http://hdl.handle.net/10919/80944.

Dowler CC, Wright DL (1995) Weed management systems for pearl millet in the southeastern United States. National Grain Pearl Millets 1: 64–71

Domínguez-Mendez R, Alcántara-de la Cruz R, Rojano-Delgado AM, Fernández-Moreno PT, Aponte R, De Prado R (2017) Multiple mechanisms are involved in new imazamox-resistant varieties of durum and soft wheat. Sci Rep 7(1):14839

Food and Agriculture Organization of the United Nations (FAO) (2025) International Year of Millets: Unleashing the Potential of Millets for the Well-Being of People and the Environment. FAO. https://www.fao.org/newsroom/detail/international-year-of-millets-unleashing-the-potential-of-millets-for-the-well-being-of-people-and-the-environment/en

Guice J, Youmans C, Rhodes A, Schultz J, Bowe S, Armel G, Harden J (2015) Provisia rice system: Weed management strategies for rice. Pages 26–29 *in* Proceedings of the Southern Weed Science Society 68th Annual Meeting, Hyatt Regency, Savannah, GA: Southern Weed Science Society

Gupta VP, Bhatnagar SK (2006) Pearlmillet. In: Plant Genetic Resources: Foodgrain Crops. Indian Council of Agricultural Research, pp 186

Gupta S, Govintharaj P (2023) Inheritance and allelism of brown midrib trait introgressed in agronomically promising backgrounds in pearl millet (*Pennisetum glaucum* (L.) R. Br.). Czech J Genet Plant Breed 59(3): 176–187

Geetha KN, Shankar AG, Mishra JS, Dubey RP, Sondhia S, Bai SK, Sinchana JK, Vidyashree BS, Tilak K (2024) Weed management under climate change in future grain millets. Indian J Weed Sci 56:439–448

Govindaraj M, Pujar M (2023) Pearl Millet. In: Compendium of Crop Genome Designing for Nutraceuticals. Springer Nature Singapore, pp 1–24

Govindaraj M, Pujar M (2024) Pearl Millet Genetic Improvement for Food and Nutrition Security. In: Pearl Millet: A Resilient Cereal Crop for Food, Nutrition, and Climate Security. Springer Nature Singapore, pp 53–79

Harinarayana G, Melkania NP, Reddy BV, Gupta SK, Rai KN, Kumar PS (2005) Forage potential of sorghum and pearl millet. In: Forage Potential of Sorghum and Pearl Millet. Academic Press, pp 292–321

Hay MM, Albers JJ, Dille JA, Peterson DE (2019) Control of atrazine-resistant Palmer amaranth (*Amaranthus palmeri*) in double-crop grain sorghum. Weed Technol 33:115–122

Heap I (2024) The International Herbicide-Resistant Weed Database. Accessed: November 15, 2024. Available at www.weedscience.org

Hennigh DS, Al-Khatib K, Tuinstra MR (2010) Postemergence weed control in acetolactate synthase–resistant grain sorghum. Weed Technol 24(3): 219–225

Howarth CJ, Rattunde EW, Bidinger FR, Harrid D (1996) Seedling survival of abiotic stress: sorghum and pearl millet. In: Proceedings of the International Conference on Genetic enhancement of sorghum and pearl millet

Iowa State University (2020) Extension and Outreach, Alternative Agriculture, Pearl Millet. https://www.extension.iastate.edu/alternativeag/pearl-millet. Accessed: February 5, 2025

Janak TW, Grichar WJ (2016) Weed control in corn (*Zea mays*) as influenced by preemergence herbicides. Int J Agron 2016 (1) https://doi.org/10.1155/2016/2607671

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28(1):28–38

Jia L, Jin XY, Zhao LX, Fu Y, Ye F (2022) Research progress in the design and synthesis of herbicide safeners: A review. J Agric Food Chem 70:5499–5515

Joshi J, Kumar SS, Rout RK, Rao PS (2025) Millet processing: prospects for climate-smart agriculture and transition from food security to nutritional security. J Future Foods 5:470–479

Jukanti AK, Gowda CL, Rai KN, Manga VK, Bhatt RK (2016) Crops that feed the world 11. Pearl Millet (*Pennisetum glaucum* L.): An important source of food security, nutrition, and health in the arid and semi-arid tropics. Food Secure 8:307–329

Kaur S, Kaur R, Chauhan BS (2018) Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. Crop Prot 103:65–72

Kaushal P, Roy AK, Malaviya DR, Bhardwaj NR, Agrawal RK (2024) Forage Pearl Millet: Issues and Strategies for Genetic Improvement. In: Pearl Millet in the 21st Century: Food-Nutrition-Climate Resilience-Improved Livelihoods. Springer Nature Singapore, pp 279–304

Kavitha S, Parimalavalli R (2014) Effect of processing methods on proximate composition of cereal and legume flours. Food Sci Indian J Res Food Sci Nutr 1:1–5

Khairwal IS, Rai KN, Diwakar B, Sharma YK, Rajpurohit BS, Nirwan B, Bhattacharjee R (2007) Pearl millet crop management and seed production manual. ICRISAT, Patancheru, India

Kohrt JR, Sprague CL (2017) Herbicide management strategies in field corn for a three-way herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) population. Weed Technol 31:364–372

Kumar V, Jha P (2017) First report of $Ser_{653}Asn$ mutation endowing high-level resistance to imazamox in downy brome (*Bromus tectorum* L.). Pest Manage Sci 73(12): 2585–2591

Kumar V, Liu R, Manuchehri M R, Westra E P, Gaines T A, Shelton C W (2021) Feral rye control in quizalofop-resistant wheat in central Great Plains. Agronomy J 113(1): 407–418

Kumar V, Liu R, Jhala AJ, Jha P, Manuchehri M (2021a) Palmer amaranth (*Amaranthus palmeri*) control in postharvest wheat stubble in the Central Great Plains. Weed Technol 35(6):945–949

Kumar V, Effertz I, Lambert T, Liu R, Bean B (2021b) Efficacy of Imiflex, Zest, and Assure II on green foxtail control. Kansas Agricultural Experiment Station Research Reports: Vol 7: Iss 5. https://doi.org/10.4148/2378-5977.8087

Kumar A, Singh D, Mahapatra S K, (2022) Energy and carbon budgeting of the pearl millet-wheat cropping system for environmentally sustainable agricultural land use planning in the rainfed semi-arid agro-ecosystem of Aravalli foothills. Energy 246:123-389

Kumar V, Tugoo MZ, Jha P, DiTommaso A, Al-Khatib K (2023a) Weed Management in Pearl Millet (*Pennisetum glaucum* (L.) R. Br.): Challenges and Opportunities. In Pearl Millet: A Resilient Crop for Food, Nutrition and Climate Security. Monograph (Eds. Perumal R, Prasad PVV, Satyavathi CT, Govindaraj M, Tenkouano A), Wiley Publishers, Alliance of Crop, Soil and Environmental Science Societies (ACSESS), ASA-CSSA-SSSA, Madison, Wisconsin, USA

Kumar V, Liu R, Chauhan D, Perumal R, Morran S, Gaines TA, Jha P (2023b) Characterization of imazamox-resistant shattercane (*Sorghum bicolor* L.) populations from Kansas. Weed Technol 37(4):376–382

Liebman MA, Staver CP, Mohler CL (2001) Crop diversification for weed management. In: Ecological Management of Agricultural Weeds. Cambridge University Press 322–374

Mishra S (2015) Weed management in millets: Retrospect and prospects. Indian J Weed Sci 47(3): 246–253

Maman N, Mason SC, Lyon DJ, Dhungana P (2004) Yield components of pearl millet and grain sorghum across environments in the Central Great Plains. Crop Sci 44:2138–2145

McCartor MM, Rouquette Jr FM (1977) Grazing pressures and animal performance from pearl millet. Agron J 69:983–987

Mishra S (2015) Weed management in millets: Retrospect and prospects. Indian J Weed Sci 47(3): 246–253

Myers RL (2002) Alternative crop guide: pearl millet. Jefferson Institute. Washington, DC http://www.Jeffersonian.org Accessed: Sep 15, 2024

Nambiar VS, Dhaduk JJ, Neha S, Shahu T, Desai R (2011) Potential functional implications of pearl millet (*Pennisetum glaucum*) in health and disease. J Appl Pharm Sci 1(10): 62–67

Newman Y, Jennings E, Vendramini J, Blount A (2010) Pearl millet (*Pennisetum glaucum*): Overview and management. SSAGR-337, one of a series of the Agronomy Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, 1-6

Nibhoria A, Kumar M, Arya RK, Siroha AK (2024) Pearl millet for good health and nutrition–An overview. CABI Rev 19:1

Parker C (1966) The importance of shoot entry in the action of herbicides applied to the soil. Weeds 14(2): 117–121

Paroda R, Agrawal A, Tripathi K (2024) Plant Genetic Resources for Adaptation to Climate Change in Drylands. In: Climate Change and Sustainable Agro-Ecology in Global Drylands. CABI, pp 77–101

Perumal R, Prasad PVV, Satyavathi T, Govindaraj M, Tenkouano A (2024) Pearl Millet: A Resilient Cereal Crop for Food, Nutrition, and Climate Security. 1st ed. ASA-CSSA-SSSA, Madison, WI, pp 1–21

Prasad PVV, Bheemanahalli R, Jagadish SVK (2017) Field crops and the fear of heat stress—Opportunities, challenges and future directions. Field Crops Res 200:114–121

Prasad PVV, Djanaguiraman M, Stewart ZP, Ciampitti IA (2020) Agroclimatology of maize, sorghum, and pearl millet. Agroclimatology: linking agriculture to climate. 60:201–241

Rai KN, Gowda CL, Reddy BV, Sehgal S (2008) Adaptation and potential uses of sorghum and pearl millet in alternative and health foods. Compr Rev Food Sci Food Saf 7:320–396

Rai KN, Yadav OP, Gupta SK, Mahala RS (2012) Emerging research priorities in pearl millet. J SAT Agric Res 10:1–4 http://ejournal.icrisat.org/index.htm

Raj S, Chaudhary S, Ghule NS, Baral K, Padhan SR, Gawande KN, Singh V (2024) Sustainable farming and soil health enhancement through millet cultivation: A review. Int J Plant Soil Sci 36:222–233

Ramalingam AP, Rathinagiri A, Serba DD, Madasamy P, Muthurajan R, Prasad PVV, Perumal R (2024) Drought tolerance and grain yield performance of genetically diverse pearl millet [*Pennisetum glaucum* (L.) R. Br.] seed and restorer parental lines. Crop Sci 64(5): 2552-2568 http://doi.org/10.1002/csc2.21271

Rai KN, Gowda CL, Reddy BV, Sehgal S (2008) Adaptation and potential uses of sorghum and pearl millet in alternative and health foods. Compr Rev Food Sci Food Saf 7:320–396.

Raj S, Chaudhary S, Ghule NS, Baral K, Padhan SR, Gawande KN, Singh V (2024) Sustainable farming and soil health enhancement through millet cultivation: A review. Int J Plant Soil Sci 36:222–233

Ravi S, Rao KN, Jadhav RL, Bhat SN, Shankar KA (2023) Effect of graded levels of nitrogen with iron and zinc nutrition on growth, yield and quality of pearl millet (Pennisetum glaucum L.). Int J Environ Clim Change 13:2425–2433

R Core Team (2023): R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Reddy SS, Stahlman PW, Geier PW, Charvat LD, Wilson RG, Moechnig MJ (2014) Tolerance of foxtail, proso and pearl millets to saflufenacil. Crop Protect 57:57–62.

Ritz C, Baty F, Streibig JC, Gerhard D (2015) Dose-response analysis using R. PloS one, Dec 30;10(12):e0146021

Sade FO (2009) Proximate, antinutritional factors and functional properties of processed pearl millet (*Pennisetum glaucum*) J Food Technol 7:92–97

Satyavathi CT, Ambawat S, Khandelwal V, Srivastava RK (2021) Pearl millet: a climate-resilient nutricereal for mitigating hidden hunger and providing nutritional security. Front Plant Sci 12:659–938

Satyavathi CT, Ambawat S, Thirunavukkarasu N, Khandelwal V, Reddy S, Narala A (2024) Global Production, Status, and Utilization Pattern of Pearl Millet. In: Pearl Millet: A Resilient Cereal Crop for Food, Nutrition, and Climate Security. Springer Nature Singapore, pp 1–21

Serba DD, Perumal R, Tesso TT, Min D (2017) Status of global pearl millet breeding programs and the way forward. Crop Sci 57(6): 2891–2905

Serba DD, Yadav RS, Varshney RK, Gupta SK, Mahalingam G, Srivastava RK, Gupta R, Perumal R, Tesso TT (2020) Genomic designing of pearl millet: A resilient crop for arid and semi-arid environments. Genomic designing of climate-smart cereal crops. 221–286

Sine B, Ndiaye A, Kanfany G, Grondin A, Ndiaye A, Faye A, Sy O, Diack O, Kane NA, Laplaze L (2024) Physiological and Molecular Bases of Drought and Heat Tolerance in Pearl Millet. In: Pearl Millet in the 21st Century: Food-Nutrition-Climate Resilience-Improved Livelihoods. Springer Nature Singapore, 247–278

Shaner DL, Beckie HJ (2014) The future for weed control and technology. Pest Manag Sci 70(9):1329–1339

Sharma A, Agrawal S, Chanu KP, Bopche V, Rattan A, Sharma A, Maisnam G, Gaikwad D (2024) Millets: A Climate-Resilient Nutricereals for Mitigating Hidden Hunger and Providing Nutritional Security. In: Millets: The Multi-Cereal Paradigm for Food Sustainability. Springer Nature Switzerland 43–56

Sharma OL, Jain NK (2003) Integrated weed management in pearl millet (Pennisetum glaucum). Indian J Weed Sci 35:134–135

Sharma KL, Grace JK, Chandrika MS, Vittal KP, Singh SP, Nema AK, Chauhan SP, Maruthi Sankar G, Mandal UK, Korwar GR, Venkateswarlu B (2014) Effects of Soil Management Practices on Key Soil Quality Indicators and Indices in Pearl Millet (*Pennisetum americanum* (L.) Leeke)–Based System in Hot Semi-arid Inceptisols. Commun Soil Sci Plant Anal 45:785–809

Shukla P, Shukla S, Pandey K, Choudhary P, Rajasekaran R, Muthamilarasan M (2024) Genetics and Genomics of Kodo Millet (*Paspalum scrobiculatum* L.). In: Genetics and Genomics of High-Altitude Crops. Springer Nature Singapore 47–63

Starkey C (2015) Use of HPPD-inhibiting herbicides for control of common weeds in Arkansas and current status of herbicide-resistance among *Echinochloa* populations in Arkansas. MS thesis. Fayetteville, AR: University of Arkansas

Sollenberger LE, Vendramini JMB, Pedreira CGS, Rios EF (2020) Warm-season grasses for humid areas. Pages 331-345 *in* Moore KJ, Collins M, Nelson CJ, Redfearn DD, eds. Forages: The Science of Grassland Agriculture. John Wiley & Sons Ltd. https://doi.org/10.1002/9781119436669.ch18

Srivastava RK, Singh RB, Pujarula VL, Bollam S, Pusuluri M, Chellapilla TS, Yadav RS, Gupta R (2020) Genome-wide association studies and genomic selection in pearl millet: Advances and prospects. Front Genet 10:1389

Swanton CE, Chandler K (1990) Control of wild-proso millet (*Panicum miliaceum*) with imazethapyr. Weed Technol 4: 446–450

Swarna R, Jinu J, Dheeraj C, Talwar HS (2024) Salinity Stress in Pearl Millet: From Physiological to Molecular Responses. In: Pearl Millet in the 21st Century: Food-Nutrition-Climate Resilience-Improved Livelihoods. Springer Nature Singapore 361–394

Todd OE, Creech CF, Kumar V, Mahood A, Peirce E (2024) Future outlook of dryland crop production systems in the semi-arid High Plains amid climate change. Outlook Pest Manag DOI: https://doi.org/10.1564/v35

Tonapi VA, Thirunavukkarasu N, Gupta SK, Gangashetty PI, Yadav OP (2024) Pearl Millet in the 21st Century. Springer Nature Singapore 1–33

Tugoo MZ, Kumar V, Ramalingam AP, et al. (2025) Sensitivity of pearl millet (*Pennisetum glaucum* [L.] R. Br.) parental lines to POST herbicides: Clethodim, quizalofop-P-ethyl, imazamox and nicosulfuron. Weed Technol doi:10.1017/wet.2025.11

Uppal R K, Wani SP, Garg K K, Alagarswamy G (2015) Balanced nutrition increases yield of pearl millet under drought. Field Crops Res 177: 86–97

Upadhyaya HD, Reddy KN, Ahmed MI, Kumar V, Gumma MK, Ramachandran S (2017) Geographical distribution of traits and diversity in the world collection of pearl millet [*Pennisetum glaucum* (L.) R. Br., synonym: *Cenchrus americanus* (L.) Morrone] landraces conserved at the ICRISAT genebank. Genet Resour Crop Evol 64:1365–1381

U.S. Department of Agriculture. (2024) Crop Explorer, Crop View, Commodity View. https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx?cropid=0459100. Accessed: February 3, 2025

Yadav HP, Gupta SK, Rajpurohit BS, Pareek N (2016) Pearl millet. In: Broadening the Genetic Base of Grain Cereals. Indian Institute of Wheat and Barley Research 205–224

Yadav OP, Gupta SK, Govindaraj M, Singh DV, Verma A, Sharma R, Mahala RS, Srivastava SK, Birthal PS (2024) Strategies for enhancing productivity, resilience, nutritional quality, and consumption of pearl millet [*Pennisetum glaucum* (L.) R. Br.] for food and nutritional security in India. Crop Sci 64:2485–2503

Yadav OP, Gupta SK, Mahala RS, Ramalingam AP, Parray SA, Perumal R (2024) Pearl millet hybrid development and seed production. Pearl millet: A resilient cereal crop for food, nutrition, and climate security 165–205

Wilson JP, Hanna WW, Gascho GJ (1996) Pearl millet grain yield loss from rust infection. J Prod Agric 9(4): 543–545

Walsh CA, Lundgren MR (2024) Nutritional quality of photosynthetically diverse crops under future climates. Plants, People, Planet 6(6): 1272–1283