Late-season Glufosinate applications to manage herbicide-resistant Palmer amaranth in soybean

by

FNU Lalit Mohan

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Major Professor
Dr. Sarah Ganske

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Abstract

Palmer amaranth (*Amaranthus palmeri* S. Watson) is among the most economically detrimental weed in U.S. soybean production, and the accumulation of herbicide resistance across multiple sites of action has reduced the number of consistently effective postemergence options available to growers. In Kansas, glufosinate and 2,4-D choline applied in Enlist E3 soybean remain important postemergence tools for managing resistant populations. However, two practical challenges can limit their reliability: single glufosinate applications often fail to control large Palmer amaranth, and glufosinate efficacy is sensitive to environmental conditions at the time of spraying. This thesis investigated both problems through replicated field experiments conducted at two Kansas locations during 2024 and 2025. The first study compared single and sequential postemergence applications of glufosinate (0.59 kg ai ha^{-1}) alone and with 2,4-D choline (0.53 kg ae ha^{-1}) targeting 20 to 30 cm Palmer amaranth. Sequential programs outperformed single applications in both years, improving control by 3.6 percentage points in 2024 (99 versus 95%; $p < 0.0001$) and 12 percentage points in 2025 (98 versus 86%; $p < 0.0001$). Neither the herbicide composition, application sequence, nor interval between passes (3, 10, or 14 days) influenced final control among sequential programs. At Hays in 2025, where treatment separation was greatest, sequential programs also resulted in greater yield than single applications (1,459 versus 1,143 kg ha^{-1}; $p = 0.0006$) and reduced Palmer amaranth biomass (12.8 versus 45.6 g m^{-2}; $p = 0.001$). These results indicate that the second application was more important than herbicide composition or interval within the sequential programs evaluated. The second study tested whether Delta-T, a single-value index of atmospheric evaporative demand calculated from dry-bulb and wet-bulb temperature, could predict glufosinate performance under field conditions. Glufosinate alone and with 2,4-D choline were each applied at 93 and 187 L ha-

[1] across multiple dates to capture a range of Delta-T values. At Manhattan 2024, where conditions spanned both optimal and high Delta-T (3.7 to 12.8 C), applications within the recommended 2 to 8 C range achieved 92% control with minimal variability, while applications above 8 C averaged only 59% with high plot-to-plot inconsistency. Each 1 C increase in Delta-T reduced control by 3.9 percentage points. At Hays 2025, however, all applications fell within the optimal Delta-T window, yet mean control reached only 68%. At this site, adding 2,4-D choline (73 versus 61%) and increasing carrier volume (75 versus 59%) both improved outcomes. Low pre-application rainfall and reduced solar radiation, not spray-day Delta-T, explained the poor performance. At Manhattan 2025, where environmental conditions were consistently favorable, all treatments achieved 87% control regardless of herbicide composition or carrier volume. Delta-T is a practical field tool for deciding when to spray, but it cannot account for the cumulative environmental stress a weed population has experienced before the sprayer arrives.

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Chapter 1 - Introduction and Literature review

1.1 Soybean Production and Weed Management Challenges

Soybean [*Glycine max (L.) Merr.*] is a major commodity crop in the United States, with nationwide production reaching 4.37 billion bushels in 2024 across 82.5 million harvested acres at an average yield of 50.7 bushels per acre. Kansas ranks eleventh nationally in soybean production, contributing 155 million bushels from 4.42 million harvested acres in 2024, with yields averaging 35 bushels per acre (USDA-NASS 2025; Kansas Soybean Commission 2025). The eastern third of Kansas contains the most productive soybean acreage due to favorable precipitation patterns, while production declines westward where drier conditions limit crop establishment and productivity.

Despite the scale and economic importance of soybean production in the state, weed interference remains a primary biological constraint across all regions. Uncontrolled weed populations reduce yield through direct competition for light, water, and nutrients, while also complicating harvest operations and diminishing grain quality. Soltani et al. (2017) estimated that, in the absence of weed management, weed interference could account for approximately $16.2 billion in annual soybean yield losses across North America, in addition to roughly $1 billion in weed control costs. These losses are largely determined by the timing of weed removal relative to crop development. The critical period for weed control in soybean, defined as the interval during which weed interference causes economically significant yield reduction, has been well established. Van Acker et al. (1993) reported that a weed-free period through the V4 growth stage, approximately 30 days after emergence, was adequate to prevent yield losses exceeding 2.5%, although the critical time of weed removal varied from V2 to R3 (approximately 9 to 38 days after emergence) depending on location and year. Delayed weed removal during this period results in yield losses that subsequent management cannot fully recover.

Among the diverse weed species infesting soybean, some present a greater threat than others because of their competitive ability, prolonged emergence, high seed production, and increasing incidence of herbicide resistance. In recent decades, Palmer amaranth (*Amaranthus palmeri* S. Watson) has emerged as one of the most problematic of these species across U.S. row-crop production systems. Its rapid growth, aggressive resource capture, and capacity to survive commonly used herbicide programs have elevated it from a regional weed concern to a major constraint on soybean production. Accordingly, understanding the biology, competitive ability, and management challenges associated with Palmer amaranth is essential for developing effective weed control strategies in Kansas soybean systems.

1.2 Palmer Amaranth and Its Competitive Characteristics

Palmer amaranth is among the most problematic weed species affecting agronomic production in the United States, with widespread impacts across multiple cropping systems. The Weed Science Society of America ranked Palmer amaranth as the most troublesome weed in broadleaf cropping systems in 2017, reflecting its economic and management consequences in U.S. agriculture (Van Wychen 2016). Consistent with this ranking, published syntheses describe Palmer amaranth as a highly competitive, rapidly growing, and prolific seed-producing species that is well adapted to modern U.S. row-crop environments (Ward et al. 2013).

1.2.1 Growth Rate and Morphological Advantages

Palmer amaranth possesses exceptional growth characteristics that provide competitive advantages over both crops and other weed species. Horak and Loughin (2000) documented height increases of 0.18 to 0.21 cm per growing degree day, substantially faster than redroot pigweed (*Amaranthus retroflexus* L.) and common waterhemp (*Amaranthus tuberculatus* [Moq.] J.D. Sauer), and under optimal conditions, growth rates can reach 4.2 mm per degree day (Norsworthy et al. 2008). This rapid vertical growth enables Palmer amaranth to overtop crop canopies and intercept the photosynthetically active radiation required for crop development.

The competitive advantage is further supported by the C4 photosynthetic pathway, which confers physiological advantages under high-temperature and high-light conditions typical of midsummer in soybean production regions. Ehleringer (1983) reported carbon dioxide assimilation rates in Palmer amaranth exceeding those of most crop species, with leaves capable of tracking solar movement throughout the day to maximize photosynthetic efficiency. Belowground, Palmer amaranth allocates a greater proportion of total biomass to root production than soybean and exhibits root traits such as greater root length and finer roots, which likely enhance soil water and nutrient capture under competitive conditions (Wright et al. 1999). Together, these aboveground and belowground traits allow Palmer amaranth to dominate resource acquisition across multiple competitive dimensions simultaneously.

1.2.2 Reproductive Capacity and Seed Bank Persistence

The fecundity of Palmer amaranth is well documented, with previous literature suggesting that it can produce large numbers of seeds under field conditions reaching up to 613,000 seeds per plant depending on cropping system and emergence timing (Mahoney et al. 2021). This prolific seed production is compounded by the fact that Palmer amaranth retains seed at soybean maturity, allowing late season escapes to contribute directly to the soil seedbank and complicate long-term management (Schwartz-Lazaro et al. 2016). Beyond sheer fecundity, the dioecious reproductive system of Palmer amaranth promotes obligate outcrossing and maintains high levels of genetic diversity within populations, which can facilitate rapid adaptation to repeated herbicide selection pressure (Ward et al. 2013)

1.2.3 Yield Impact in Soybean

Interference caused by Palmer amaranth causes substantial soybean yield reductions when control measures fail or are delayed. In Kansas, Bensch et al. (2003) reported that soybean yield loss increased with Palmer amaranth density, reaching approximately 79% at eight plants per meter of row when weeds emerged at soybean planting; however, later-emerging cohorts did not significantly reduce yield. Korres et al. (2019) similarly demonstrated that yield reductions were greatest when Palmer amaranth established at or within one week after crop emergence, with progressively diminished competitive impact at later establishment timings. Although these later-emerging plants contributed less to direct yield loss, they remained important sources of seed replenishment to the soil seedbank, sustaining future infestation pressure. The interaction between density and emergence timing underscores that preventing early-season Palmer amaranth interference is a fundamental component of effective soybean management programs, while also highlighting that escapes at any growth stage carry long-term consequences through seedbank replenishment.

1.3 Herbicide Resistance Evolution in Palmer Amaranth

Weed management in soybean historically has relied on a combination of cultural, mechanical, and chemical tactics; however, the efficiency, scalability, and broad-spectrum activity of herbicides made chemical control the dominant foundation of modern soybean weed management programs. As herbicide-tolerant crop technologies expanded, repeated reliance on the same herbicide sites of action imposed intense and recurring selection pressure on weed populations. Over time, this selection favored individuals able to survive treatment, leading to the evolution and spread of herbicide-resistant biotypes. Palmer amaranth has been particularly successful in this process because its biological attributes increase both the probability of resistance evolution and the speed at which resistant alleles can spread through populations.

As a result of repeated herbicide selection, Palmer amaranth has evolved resistance to herbicides from up to ten WSSA sites of action across reported U.S. populations, placing it among the most herbicide-resistant dicot weed species in North America (Heap 2026). Few new herbicide sites of action have been commercialized in recent decades (Duke 2012), which increases reliance on existing chemistries and increased the importance of preserving their long-term efficacy through resistance management. The first documented case of herbicide resistance in Palmer amaranth was to dinitroaniline (microtubule-inhibiting) herbicides, confirmed in South Carolina in the early 1990s (Gossett et al. 1992). Resistance to ALS-inhibiting herbicides followed shortly in Kansas, with populations resistant to imazethapyr and thifensulfuron were identified (Horak and Peterson 1995). Follow-up research reported that ALS-resistant populations exhibited reduced control by multiple ALS-inhibiting herbicides, indicating broad cross-resistance within the ALS class (Gaeddert et al. 1997).

The commercialization of glyphosate-resistant crops in 1996 and subsequent near-exclusive reliance on glyphosate for postemergence weed control imposed intense selection pressure on Palmer amaranth populations. Glyphosate-resistant Palmer amaranth was first confirmed in Georgia (Culpepper et al. 2006), with the resistance mechanism identified as amplification of the EPSPS gene, the first documented case of gene amplification conferring herbicide resistance in any plant species (Gaines et al. 2010). By the mid-2020s, glyphosate-resistant Palmer amaranth had been reported across a broad range of U.S. soybean and row-crop production regions, with confirmed resistance documented in more than two dozen states according to the International Herbicide-Resistant Weed Database (Heap 2026).

As growers shifted to alternative chemistries, Palmer amaranth populations responded with resistance to those herbicides as well. Resistance to PPO-inhibiting herbicides was confirmed in Arkansas, where a glycine deletion at position 210 (ΔG210) in the PPX2 gene was identified as the target-site mechanism (Salas et al. 2016), with additional target-site mutations subsequently documented (Salas-Perez et al. 2017; Rangani et al. 2019). Resistance to HPPD-inhibiting herbicides was reported in Kansas populations, mediated by enhanced metabolism through cytochrome P450 enzymes rather than target-site modification (Nakka et al. 2017). Notably, a single Palmer amaranth population from Kansas was reported resistant to six SOAs, including ALS-, PSII-, EPSPS-, PPO-, HPPD-inhibitors and synthetic auxins, with metabolic resistance identified as the predominant mechanism for five of the six SOAs (Shyam et al. 2021a). The prevalence of metabolism-based non-target-site resistance (NTSR) in this population is particularly concerning because enhanced enzymatic detoxification can confer cross-resistance to chemically unrelated herbicides, including those never applied to the population (Yu and Powles 2014; Jugulam and Shyam 2019).

1.3.1 Emerging Resistance to Glufosinate

The progressive accumulation of resistance across multiple SOAs has severely narrowed postemergence chemical weed control options for Palmer amaranth in soybean. Glufosinate remains one of the few postemergence herbicides that can still provide effective control of many multiple-resistant Palmer amaranth populations, although increasing reports of reduced sensitivity and resistance threaten its continued effectiveness. Priess et al. (2022) confirmed glufosinate-resistant Palmer amaranth in Arkansas, with resistance ratios of 5.1 to 27.4 depending on the population and assessment method. This was the first confirmed case of glufosinate resistance in Palmer amaranth under field conditions. Subsequently, Jones et al. (2024) confirmed glufosinate-resistant Palmer amaranth in North Carolina, indicating that resistance to this herbicide is not geographically isolated. Werle Noe et al. (2026) further reported glufosinate resistance in waterhemp populations from Illinois, demonstrating that resistance to this herbicide is emerging across multiple Amaranthus species. As glufosinate use has increased substantially with the adoption of LibertyLink, Enlist E3, and XtendFlex trait platforms, selection pressure on Palmer amaranth populations continues to intensify.

1.4 Glufosinate: Mode of Action and Limitations

Glufosinate (2-amino-4-[hydroxy(methyl)phosphinoyl] butanoic acid) is a broad-spectrum, non-selective, and primarily contact postemergence herbicide belonging to WSSA Herbicide Group 10 that inhibits glutamine synthetase (GS; EC 6.3.1.2), the enzyme responsible for converting glutamate and ammonia into glutamine in the nitrogen assimilation pathway (Takano and Dayan 2020). Inhibition of GS results in rapid accumulation of ammonia to phytotoxic levels, disrupting amino acid biosynthesis and photorespiratory nitrogen cycling. However, recent mechanistic work has demonstrated that the rapid contact activity of glufosinate is primarily driven by the accumulation of reactive oxygen species (ROS) through disruption of both photorespiration and the light reactions of photosynthesis, with the resulting lipid peroxidation causing membrane destruction and cell death within hours of application under adequate light conditions (Takano et al. 2019). Takano and Dayan (2021) further demonstrated that GS gene expression and protein abundance were greater in the light than in the dark; mid-day application of glufosinate inhibited GS activity by more than 95% within two hours and maintained that suppression permanently, whereas dusk application achieved only 82%

inhibition, and plants recovered full GS activity within days through rapid enzyme resynthesis. This light-dependent mode of action explains the well-documented sensitivity of glufosinate performance to solar radiation intensity, relative humidity, and time of day at the time of application (Coetzer et al. 2001; Sellers et al. 2003).

Because glufosinate is highly hydrophilic and exhibits limited phloem translocation, it functions primarily as a contact herbicide, and thorough spray coverage of target foliage is essential for effective weed control (Takano and Dayan 2020). This characteristic has direct consequences for the control of Palmer amaranth, as the rapid vertical growth rate can quickly exceed the height at which glufosinate provides reliable control. Steckel et al. (1997) established that glufosinate efficacy on annual weeds is strongly influenced by both application rate and weed growth stage, with control declining substantially as weed height increased beyond 10 cm. Coetzer et al. (2002) confirmed this pattern specifically for Amaranthus species in glufosinate-resistant soybean, reporting that only sequential applications of glufosinate at 410 g ai ha^{-1} followed by 293 g ai ha^{-1} achieved greater than 80% control of Palmer amaranth, whereas single applications at those same rates were insufficient.

Beyond direct control failures, Palmer amaranth plants that survive a single glufosinate application retain the capacity for substantial reproductive output. Jones et al. (2022) documented that Palmer amaranth individuals surviving glufosinate treatment in soybean remained sufficiently fecund to contribute meaningfully to seedbank replenishment.

1.5 Sequential Application Strategies for Palmer Amaranth Control

Best management practices for herbicide resistance management emphasize targeting weeds at or below labeled sizes, utilizing multiple effective SOAs, and implementing season-long herbicide programs (Norsworthy et al. 2012). However, field conditions frequently prevent timely application. Untimely rainfall, high winds that exceed label restrictions, and narrow operational windows common during Kansas summers can allow Palmer amaranth to emerge and surpass the 10 cm threshold before a grower can respond. Horak and Loughin (2000) showed that Palmer amaranth exhibited the greatest height increase among four Amaranthus species and ranked among the highest for plant volume, dry weight, leaf area, specific leaf area, and relative growth rate, supporting its strong competitive ability and narrow herbicide application window. Even when a PRE herbicide has been applied, escapes and late-emerging cohorts may outgrow labeled sizes by the time POST applications begin. In these situations, an aggressive postemergence program becomes the most practical path forward (Meyer and Norsworthy 2020).

Research across multiple geographies has consistently shown that sequential glufosinate applications are needed when large Palmer amaranth is present. Meyer and Norsworthy (2020) found that in LibertyLink soybean in Arkansas, sequential glufosinate applications were superior to single applications regardless of rate, with control optimized at the 7-to-10-day interval. In cotton, Randell et al. (2020) demonstrated that sequential glufosinate applications at 1-to-7-day intervals controlled 15 to 20 cm Palmer amaranth at 98 to 99%, compared to 70 to 88% at 10 to 14 day intervals. Priess et al. (2022) reported that sequential applications in XtendFlex cotton improved Palmer amaranth control by 11 to 17 percentage points over single applications, and that programs incorporating two SOAs were superior to repeated use of a single SOA for mitigating resistance risk. Kumar et al. (2023) reported that all sequential glufosinate programs provided 87 to 93% control of tall (70 to 90 cm) glyphosate-resistant Palmer amaranth, while a single standard-rate application did not exceed 84%. Foster et al. (2024), working on dicamba-resistant Palmer amaranth in Tennessee, found that control increased as the interval between sequential applications of 2,4-D or dicamba with glufosinate decreased from 21 to 7 days, and that the greatest control in a 2,4-D system was achieved when 2,4-D was applied first.

The commercialization of Enlist E3 soybean, a trait platform conferring crop tolerance to 2,4-D choline, glufosinate, and glyphosate, has expanded the range of postemergence herbicide options available for Palmer amaranth management in soybean. Within the Enlist system, 2,4-D choline can be applied postemergence through the R1 growth stage either alone or in tank mixture with glufosinate, providing two distinct sites of action targeting the same weed population in a single pass. The synthetic auxin 2,4-D acts through a fundamentally different mechanism than glufosinate, mimicking endogenous auxin signaling to induce uncontrolled cell elongation, vascular tissue disruption, and eventual plant death. Because 2,4-D translocates systemically through the phloem, it can reach plant tissues that a contact herbicide like glufosinate cannot, which can compensate for the decline in glufosinate activity on larger plants. Craigmyle et al. (2013) demonstrated that mixtures of glufosinate and 2,4-D were more effective in controlling common waterhemp, Asiatic dayflower, and barnyard grass than either herbicide alone, with higher magnitude of difference as the height increased. Furthermore, two-pass postemergence programs incorporating 2,4-D with glufosinate improved common waterhemp control compared to two-pass programs containing glufosinate alone. Meyer et al. (2015) confirmed in a multi-state evaluation that including a synthetic-auxin herbicide in the late POST application improved control of both Palmer amaranth and waterhemp compared to programs that did not include an auxin at that timing.

In Enlist E3 soybean specifically, Shyam et al. (2021b) tested sequential postemergence programs in Nebraska and reported that sequential applications of either 2,4-D choline or glufosinate provided 85 to 92% control of glyphosate-resistant Palmer amaranth, establishing both herbicides as effective POST options within this system. Ogden and Dotray (2022) found in West Texas that 2,4-D choline plus glyphosate followed by glufosinate provided the greatest level of Palmer amaranth control at both weed sizes evaluated, and that Palmer amaranth control was not influenced by sequential application order when glufosinate and 2,4-D choline were used together.

1.6 Environmental Factors and Carrier Volume Affecting Glufosinate Efficacy

Because glufosinate functions primarily through light-dependent accumulation of reactive oxygen species (Takano et al. 2019), its activity is inherently tied to solar radiation intensity, and applications made under low light conditions or at dawn and dusk consistently produce inferior weed control compared to midday applications under full sunlight. The efficacy of glufosinate is strongly influenced by environmental conditions at and around the time of application. Sellers et al. (2003) documented that glufosinate efficacy was reduced by diurnal fluctuations in plant physiology and by changes in leaf angle that decreased spray interception later in the day. Stopps et al. (2013) similarly reported species-specific time-of-day effects across multiple postemergence herbicides in Ontario soybean, with weed control generally reduced when applications were made at 6:00 AM, 9:00 PM, or midnight. Montgomery et al. (2017) confirmed this pattern in field trials on horseweed, reporting that glufosinate applied at midday provided 92% control at 28 days after treatment, compared with 63% from sunrise applications and 79% from sunset applications.

In addition to time of day, relative humidity (RH) can affect the rate at which spray droplets dry on leaf surfaces, optimum RH increases the leaf-droplet contact time and low humidity accelerates droplet evaporation, reducing the time available for foliar absorption of the herbicide. Coetzer et al. (2001) demonstrated that relative humidity had a greater effect on glufosinate toxicity to Palmer amaranth, redroot pigweed, and common waterhemp than did temperature. At 90% relative humidity, all rates of glufosinate caused severe leaf wilting within one day after treatment, whereas at 35% relative humidity, comparable symptoms were delayed by two to three days and control at 14 days after treatment was reduced by 30 to 50 percentage points depending on species and rate. Importantly, the mechanism was not a reduction in absorption but rather a reduction in translocation: at 90% RH, up to 31% of absorbed glufosinate translocated out of the treated leaf, compared with less than 6% at 35% RH. Ramsey et al. (2002) extended these findings in wild oat, showing that even 30 minutes of exposure to high RH before and after spraying increased glufosinate efficacy compared with continuous low-humidity conditions. Critically, they demonstrated that post-application humidity, rather than pre-application humidity, was the critical period, proposing that high RH slows spray droplet drying and thereby prolongs the period of cuticular penetration.

Temperature similarly modulates glufosinate performance. Kumaratilake and Preston (2005) reported that low temperatures reduced both glufosinate activity and translocation in wild radish. Pre-application drought conditions may further reduce POST herbicide performance, as drought stress can alter plant physiology and reduce herbicide efficacy in a species-dependent manner (Alizade et al. 2021).

Although previous research has demonstrated that glufosinate efficacy responds to multiple environmental variables, many of these variables are difficult to integrate into real-time field decisions. Temperature and humidity at the time of application are readily measurable in the field and directly influence droplet behavior, drying time, and plant surface conditions, making them the most practical basis for a field-use decision tool. Although temperature and relative humidity are often discussed separately, their influence on spray application is inherently interactive. Together, they determine the evaporative demand of the atmosphere, which governs how rapidly droplets lose moisture after leaving the nozzle and how long they remain on the leaf surface before drying. As temperature increases and relative humidity declines, droplet evaporation accelerates, reducing the opportunity for retention and absorption of contact herbicides such as glufosinate. Because these two variables operate simultaneously under field conditions, an integrated metric that reflects their combined effect may provide a more practical basis for real-time application decisions than either variable alone.

Delta-T, defined as the difference between the dry-bulb air temperature and the wet-bulb temperature, integrates application-time temperature and humidity into a single value describing the evaporative demand of the atmosphere during spraying. Delta-T has been widely adopted in Australian spray application guidelines through the Grains Research and Development Corporation (GRDC 2025; Sprayers 101). When Delta-T is low (below 2 C), the air is near saturation and spray conditions are often unfavorable because of increased drift risk. When Delta-T falls within the recommended range of 2 to 8 C, conditions generally balance droplet survival with adequate coverage. Values between 8 and 10 C are generally treated as a caution zone, indicating increasingly evaporative conditions. When Delta-T exceeds 10 C, the air is hot and dry, droplets evaporate rapidly, and herbicide performance may decline (GRDC 2025).

However, the Delta-T thresholds used in Australian spray application guidelines originate primarily from extension and operational experience rather than from controlled peer-reviewed experiments quantifying their relationship to herbicide efficacy on specific weed species.

In addition to environmental conditions, carrier volume at application has direct implications for spray coverage and weed control. Because glufosinate is a contact herbicide with limited translocation, thorough coverage of target foliage is essential. The Liberty 280 SL label recommends a minimum spray volume of 140 L ha^{-1} for ground applications and an increase to 187 L ha^{-1} for better coverage of large weeds, dense foliage, or when using larger spray droplets (Anonymous 2022). Butts et al. (2018) evaluated the interaction between spray droplet size and carrier volume on glufosinate efficacy across six site-years in Mississippi, Nebraska, and North Dakota and reported that increased carrier volume (187 L ha^{-1}) buffered the negative effect of larger droplet sizes on weed control.

1.7 Research Scope

Collectively, the effective management of large Palmer amaranth in Kansas soybean production will require postemergence programs that integrate multiple effective sites of action while accounting for the environmental conditions that influence glufosinate performance. Glufosinate remains one of the few postemergence herbicides with activity on many multiple-resistant Palmer amaranth populations, but its contact-dependent mode of action imposes biological limitations that single applications cannot reliably overcome when targeting large, escaped plants. The Enlist E3 soybean platform provides the opportunity to combine glufosinate with 2,4-D choline, thereby adding a systemic component to the postemergence program, yet field-tested guidance on how to structure and time these programs in Kansas remains limited. Likewise, although the environmental sensitivity of glufosinate is well established, the field relevance of application-time atmospheric metrics such as Delta-T and the extent to which carrier volume can offset suboptimal spray conditions across Kansas remain insufficiently resolved.

These knowledge gaps formed the basis for the research presented in this thesis. The specific objectives of each study are presented within the respective chapter.

Chapter 2: Sequential Postemergence Applications of Glufosinate and 2,4-D Choline for Control of Palmer Amaranth (*Amaranthus palmeri*) in Enlist E3 Soybean

Chapter 3: Effect of Delta-T and Carrier Volume on Glufosinate Efficacy for Palmer Amaranth (*Amaranthus palmeri*) Control in Soybean

Chapter 4: Summary and Conclusions

Chapter 2 - Sequential postemergence applications of Glufosinate and 2,4-D choline for control of Palmer amaranth (*Amaranthus palmeri*) in Enlist E3 soybean

Lalit Mohan[1], Koffi Badou-Jeremie Kouame[2], Elizabeth A. Yeager[3], and Sarah Ganske[1]*

Abstract

Palmer amaranth is one of the most problematic weeds in U.S. soybean production due to its rapid growth, prolific seed production, and ability to evolve resistance to multiple herbicide sites of action. When postemergence applications are delayed and Palmer amaranth exceeds recommended spray heights, single herbicide applications often fail to provide acceptable control. Field experiments were conducted during 2024 and 2025 at two Kansas locations (Ashland Bottoms and Hays) to evaluate single and sequential postemergence applications of glufosinate alone (0.59 kg ai ha^{-1}) and glufosinate plus 2,4-D choline (0.53 kg ae ha^{-1}) for control of late-season Palmer amaranth in Enlist E3 soybean. Treatments included two single-application programs and 12 sequential programs representing all combinations of the two herbicide options applied at 3,10 or 14 days after the initial application. The experiment was arranged as a randomized complete block design with four replications at each location-year. Sequential applications provided greater Palmer amaranth control than single applications in both years. First-pass herbicide composition, second-pass herbicide composition, and application interval did not affect final control among sequential programs in either year. At Hays in 2025, sequential programs yielded 316 kg ha^{-1}more than single applications (1,459 versus 1,143 kg ha^{-1}; $p = 0.0006$). Making a second postemergence application was more important than the specific herbicide combination or interval between applications.

Nomenclature

Glufosinate; 2,4-D choline; S-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Watson; soybean, *Glycine max* (L.) Merr.

Keywords

Enlist E3; glufosinate; herbicide resistance; Palmer amaranth; sequential application; soybean; 2,4-D choline; weed management

2.1 Introduction

Weed interference remains a major biological constraint to soybean production, reducing yield and complicating timely in-season management. Among soybean weeds, Palmer amaranth is especially problematic because of its aggressive growth, prolific seed production, and ability to evolve resistance to multiple herbicide sites of action. Palmer amaranth is ranked as the most troublesome weed in U.S. broadleaf cropping systems (Van Wychen 2016) and can reduce soybean yield by approximately 79% when it emerges at planting (Bensch et al. 2003). Its rapid growth relative to other *Amaranthus* species (Horak and Loughin 2000), seed production of up to 500,000 seeds per plant (Mahoney et al. 2021), and obligate outcrossing (Jhala et al. 2021) make it highly competitive and well adapted for rapid evolution under herbicide selection. Palmer amaranth has now evolved resistance to herbicides representing 10 sites of action in the United States (Heap 2026).

Herbicides remain the dominant tool for postemergence weed management in soybean, but repeated reliance on the same sites of action has selected for herbicide-resistant weed populations, narrowing the number of effective postemergence options. Earlier reviews noted that no new herbicide sites of action had been commercialized for decades, increasing pressure on existing herbicides (Duke 2012). In Kansas, the KCTR Palmer amaranth population was reported resistant to six sites of action through predominantly metabolic mechanisms, with only glufosinate and paraquat providing satisfactory control (Shyam et al. 2021a). Because metabolism-based resistance can confer cross-resistance to chemically unrelated herbicides (Yu and Powles 2014; Jugulam and Shyam 2019), stewardship of remaining effective postemergence (POST) herbicides is critical. Glufosinate remains one of the few postemergence herbicides that can still control many multiple-resistant Palmer amaranth populations, although resistance has now been confirmed in Arkansas and North Carolina (Priess et al. 2022; Jones et al. 2024).

The value of glufosinate can be limited by its contact activity, which reduces control as Palmer amaranth size increases beyond labeled heights. (Steckel et al. 1997; Coetzer et al. 2002). While best management practices emphasize applying a preemergence (PRE) herbicide at planting and targeting weeds at or below labeled sizes (Norsworthy et al. 2012), in practice, these ideals are not always achievable. Untimely rainfall, high winds and narrow spray windows often delay POST applications long enough for Palmer amaranth to exceed the recommended size threshold (Horak and Loughin 2000) before a grower can respond. Even when a PRE herbicide has been applied, escapes and late-emerging cohorts may outgrow labeled sizes by the time POST applications begin. In these situations, crop destruction is often not economically viable, and an aggressive POST program becomes the most practical path forward (Meyer and Norsworthy 2020). This is important because survivors of glufosinate treatment can still contribute substantially to seedbank replenishment (Jones et al. 2022). Previous studies have consistently shown that sequential applications improve control of large Palmer amaranth, including in Arkansas, Kansas, Texas, and Tennessee (Meyer and Norsworthy 2020; Kumar et al. 2023; Randell et al. 2020; Priess et al. 2022; Ogden and Dotray 2022; Foster et al. 2024).

The Enlist E3 soybean platform permits postemergence application of 2,4-D choline, glufosinate, and glyphosate, thereby providing flexibility to combine herbicides with contrasting patterns of activity. In the present study, emphasis was placed on glufosinate and 2,4-D choline because glyphosate resistance is already widespread in Palmer amaranth populations, limiting the value of glyphosate as a dependable postemergence option for large plants (Gaines et al. 2021). Within this system, glufosinate provides rapid contact activity, whereas 2,4-D contributes systemic translocation to tissues that may escape adequate spray coverage. Previous research has shown that mixtures or sequential programs containing glufosinate and 2,4-D can improve control of troublesome broadleaf weeds, including Palmer amaranth, relative to glufosinate alone (Craigmyle et al. 2013; Meyer et al. 2015; Shyam et al. 2021b; Ogden and Dotray 2022)

However, previous studies either did not systematically vary the interval between applications, did not evaluate all glufosinate versus glufosinate plus 2,4-D choline sequence combinations, or were conducted outside Enlist E3 soybean systems (Meyer and Norsworthy 2020; Priess et al. 2022; Shyam et al. 2021b; Ogden and Dotray 2022; Kumar et al. 2023; Foster et al. 2024). Therefore, the objective of this study was to evaluate single and sequential postemergence applications of glufosinate alone and glufosinate plus 2,4-D choline for control of large (20 to 30 cm) Palmer amaranth in Enlist E3 soybean, and to determine whether herbicide composition, application sequence, or interval between applications influences control across two Kansas locations over two field seasons (2024 and 2025).

2.2 Materials and Methods

Field experiments were conducted during the 2024 and 2025 growing seasons at two locations in Kansas: the Ashland Bottoms Experiment Field near Manhattan, KS (39°07'29.6"N 96°36'26.3"W) and the Western Kansas Agricultural Research Center Hays, KS (38°51'13.6"N 99°20'19.8"W). The soil at Ashland Bottoms was Reading silt loam with pH 6.5 and 2.6% organic matter. The soil at Hays was Crete silty clay loam with pH 7.2 and 2% organic matter in 2024 and pH 7.9 and 3.2% organic matter in 2025. These two locations were selected to represent the range of environmental conditions encountered across eastern and western Kansas soybean production, and because both sites have documented history of Palmer amaranth infestation.

Enlist E3 soybean variety P38Z63E was planted at Manhattan in 2024 and at Hays in both 2024 and 2025, whereas B392EE was planted at Manhattan in 2025, in 76 cm rows at a depth of approximately 5 cm at both locations. At Ashland Bottoms, soybean was planted on June 4, 2024, and May 13, 2025 at seeding rate of 296,526 seeds ha$^{-1.}$ At Hays, soybean was planted on July 10th, 2024, and June 1, 2025 at seeding rates of 387,708 seeds ha^{-1} and 385,484 seeds ha^{-1} respectively. In 2024, at Ashland Bottoms S-metolachlor (Dual Magnum, Syngenta Crop Protection LLC, Greensboro, NC) at 1 kg ai ha^{-1} was applied to all plots at planting. In 2025, neither location received a pre-emergence herbicide treatment. Individual plots measured 3×9.1m at all site-years.

The experiment was arranged as a randomized complete block design (RCBD) with four replications at each location-year. Treatments consisted of a non-treated control and 14 herbicide programs comprising single and sequential postemergence applications of glufosinate (Liberty 280 SL in 2024; Liberty Ultra in 2025; BASF Corporation, Research Triangle Park, NC) alone or in tank mixture with 2,4-D choline (Enlist One, Corteva Agriscience, Indianapolis, IN). Glufosinate was applied at 0.59 kg ai ha^{-1} and 2,4-D choline at 0.53 kg ae ha^{-1}. Ammonium sulfate (AMS) at 2.5% v/v was included with all herbicide treatments.

Single application treatments consisted of glufosinate alone (G) or glufosinate plus 2,4-D choline (G + 2,4-D) applied once to 20 to 30 cm Palmer amaranth. Sequential application treatments consisted of all four possible two-pass combinations of G and G+ 2,4-D (G fb G, G fb G+2,4-D, G+2,4-D fb G, and G+2,4-D fb G+2,4-D), with the second application occurring 3, 10, or 14 days after the initial application (DAA). The same herbicide rates were used in both the initial and sequential applications. The complete treatment structure, including herbicide products and rates, is presented in Table 2.1.

Postemergence herbicide applications were initiated when Palmer amaranth reached 20 to 30 cm in height. All herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1} at 241 kPa and an application speed of 3 km h^{-1}. Glufosinate-only treatments were applied with TeeJet Turbo TwinJet TTJ11002 nozzles (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL), and treatments that included 2,4-D choline were applied with TeeJet Air Induction Extended Range AIXR11002 nozzles (TeeJet Technologies) to comply with label requirements for drift reduction when applying 2,4-D. Air temperature, relative humidity, wind speed, and wind direction were recorded at the start and end of each application (Table 2.8).

Palmer amaranth control was visually estimated on a scale of 0 to 100%, where 0 indicated no control and 100 indicated complete plant death, relative to the non-treated control. Visual control ratings were recorded for all plots on three common dates: at 3 days after the initial application (coinciding with the first sequential application for the 3 DAA treatments), and at 2 and 4 weeks after the first sequential application. All treatments, including single applications and sequential treatments at the 10 and 14 DAA intervals, were evaluated on these same dates regardless of when their own sequential application occurred.

Palmer amaranth biomass was determined at soybean harvest. Palmer amaranth plants were collected in two 1 m^2 quadrats $plot^{-1}$, dried at 55 °C until constant weight and dry weights recorded. Soybean was harvested and grain yield was adjusted to 13 % moisture.

All data were analyzed in R version 4.4.1 (R Core Team 2024) within the RStudio environment (version 2024.09.0+375) using linear mixed-effects models fit with the lmer function from the lme4 package. Denominator degrees of freedom were approximated using the Kenward-Roger method via the lmerTest package. Estimated marginal means were computed with the emmeans package, and compact letter displays for mean separation were generated using the multcomp package at $\alpha = 0.05$.

A combined analysis across both years and locations was first conducted with treatment, year, location, and all two- and three-way interactions as fixed effects. Replication nested within location and year was included as a random effect. This model was used to test for treatment-by-year and treatment-by-location interactions in visible control ratings. A parallel combined analysis was conducted on the 12 sequential treatments only, using a five-way factorial structure with first-pass herbicide (Glufosinate or Glufosinate + 2,4-D), second-pass herbicide (Glufosinate or Glufosinate + 2,4-D), application timing (3, 10, or 14 DAA), year, and location as fully crossed fixed effects, with the same random-effect structure.

Where the treatment-by-year and treatment-by-location interactions were significant in the combined model, data were subsequently analyzed separately by year and by location. In year-specific analyses, treatment was the fixed effect, location was included as a fixed effect, and replication nested within location was the random effect. In location-specific analyses pooled across years, treatment was the fixed effect, year was included as a fixed effect, and replication nested within year was the random effect. In cases where a subset of the data contained observations from only one location (as occurred for the second-pass visual rating in 2024), location was dropped from the model and replication alone served as the random effect.

Soybean yield was first analyzed using a combined model with treatment, year, location, and all two- and three-way interactions as fixed effects, and replication nested within location and year as a random effect. Yield was analyzed within each year using a model with treatment, location, and their interaction as fixed effects and replication nested within location as a random effect. When the treatment-by-location interaction was significant, data were analyzed separately by location with treatment as the fixed effect and replication as the random effect. A planned contrast of sequential versus single application strategies was also tested at each location. Palmer amaranth biomass in 2025 was analyzed using the same approach. Biomass data from 2024 were insufficient for statistical analysis and are reported descriptively.

Visual control data were also analyzed following arcsine square root transformation, and biomass data following log(Y+1) transformation; all primary conclusions were unchanged, and untransformed results are presented for ease of interpretation as the F-test in ANOVA is robust to departures from normality, particularly with balanced designs (Blanca et al. 2017).

Within each year, five questions were addressed. First, overall treatment means for 4-week Palmer amaranth control were compared across all 14 treatments. Second, the overall benefit of a sequential application was evaluated by fitting a model with application strategy (single versus sequential) as the fixed effect, and a pairwise contrast was used to test the difference. Third, the effect of the first-pass herbicide (G or G + 2,4-D) was tested separately within single-application treatments, within sequential-application treatments, and for the second-pass visual rating taken before the sequential application was made. Fourth, application timing (3, 10, or 14 DAA) was compared among sequential treatments. Fifth, a three-way factorial model was fit to the sequential treatments with first-pass herbicide, second-pass herbicide, and application timing as fully crossed fixed effects and location as an additive fixed effect, to test all main effects and interactions among the herbicide and timing components. Identical analyses were also conducted on the 2-week visual control rating.

2.3 Results and Discussion

2.3.1 Combined Analysis

The combined analysis across both years and locations detected treatment-by-year ($p = 0.003$) and treatment-by-location ($p = 0.001$) interactions for Palmer amaranth control at 4-weeks. The three-way interaction of treatment by year by location was not significant ($p = 0.48$). Because treatment responses differed across years and locations, data were subsequently analyzed separately by year and by location.

Among the 12 sequential treatments only, the combined factorial analysis revealed no significant main effects or interactions for first-pass herbicide, second-pass herbicide, or application timing ($p > 0.10$ for all terms). Year was the only significant factor in the factorial model ($p = 0.02$), confirming that overall weed control levels differed between 2024 and 2025 but that the relative performance of herbicide combinations and timing intervals did not change.

2.3.2 Palmer Amaranth Control: 2024

At the second-pass visual rating taken before sequential applications were made, G and G + 2,4-D provided similar initial control ($p = 0.28$).

Treatment affected Palmer amaranth control at the 2-week rating in 2024 ($p = 0.004$; Table 2.2). Most sequential treatments provided 94 to 99% control. A single application of G provided 91% control at 2-weeks, which was the lowest among all treatments. The first-pass herbicide did not affect Palmer amaranth control at the 2-week rating within single-application treatments ($p = 0.37$).

Treatment affected Palmer amaranth control at the 4-week rating in 2024 ($p = 0.005$; Table 2.2). 11 out of 12 sequential treatments provided 99% control and were not different from one another. G fb G at the 3 DAA interval provided 97% control, which was not different from any sequential or single-application treatment. A single application of G + 2,4-D provided 94% control, which was less than the 11 sequential treatments at 99% but not different from G at 96% or G fb G at 3 DAA at 97%. All sequential application programs provided greater Palmer amaranth control than single applications in 2024 ($p < 0.001$). Averaged across all programs within each strategy, sequential treatments controlled Palmer amaranth 99% compared with 95% for single applications ($p < 0.0001$). This pattern is consistent with previous reports demonstrating that sequential glufosinate applications are critical for controlling large Palmer amaranth (Meyer and Norsworthy 2020; Randell et al. 2020; Priess et al. 2022).

The first-pass herbicide (G versus G + 2,4-D) did not affect Palmer amaranth control at any evaluation timing. Among single-application treatments, the two herbicide programs did not differ at the 4-week rating ($p = 0.35$). Among sequential treatments, first-pass herbicide likewise had no effect on Palmer amaranth control at the 4-week rating ($p = 0.32$). Application timing (3, 10, or 14 DAA) did not influence Palmer amaranth control at the 4-week rating among sequential treatments in 2024 ($p = 0.37$). Control was 99% across all three application intervals. The year-specific factorial model confirmed these results: no main effects or interactions among first-pass herbicide, second-pass herbicide, or application timing were significant ($p > 0.32$ for all terms). The absence of significant herbicide or timing effects within sequential programs indicates that under the conditions of this study, completing the second application was more important than the specific herbicide composition or sequence interval.

2.3.3 Palmer Amaranth Control: 2025

At the second-pass visual rating taken before sequential applications were made, G and G + 2,4-D provided similar initial control ($p = 0.67$).

Treatment affected Palmer amaranth control at the 2-week rating in 2025 ($p < 0.001$; Table 2.3). Sequential treatments ranged from 88 to 99% control at this evaluation timing, with the highest 2-week ratings among treatments applied at the 3 DAA interval (97 to 99%) and lower ratings among treatments applied at the 10 and 14 DAA intervals (88 to 96%), reflecting the shorter time for the later sequential applications to take full effect. A single application of G provided 87% control at 2-week, which was the lowest among all treatments. Among single-application treatments, G and G + 2,4-D did not differ at 2-week ($p = 0.24$), providing 87 and 91% control, respectively.

Treatment differences were more pronounced in 2025 than in 2024. Treatment affected Palmer amaranth control at the 4-week rating in 2025 ($p < 0.001$; Table 2.3). Five sequential treatments provided 99% control: G fb G at 3 DAA, G fb G + 2,4-D at 3 DAA, G + 2,4-D fb G + 2,4-D at 3 DAA, G + 2,4-D fb G + 2,4-D at 10 DAA, and G fb G + 2,4-D at 14 DAA. The remaining seven sequential treatments ranged from 96 to 98% control and were not different from the top-performing group. The single application of G + 2,4-D provided 92% control, which was intermediate between the sequential group and G alone. The single application of G provided 80% control, which was the lowest of all treatments and was significantly less than all 12 sequential programs.

The advantage of sequential over single applications was greater in 2025 than in 2024. Sequential treatments averaged 98% control compared with 86% for single applications, a difference of 12 percentage points ($p < 0.0001$). This pattern is consistent with the significant treatment-by-year interaction detected in the combined model and highlights the value of a follow-up application as a buffer against year-to-year variability in growing conditions and weed pressure.

As in 2024, the first-pass herbicide did not affect control in any analysis in 2025. Among single-application treatments, G + 2,4-D numerically outperformed G alone (92 versus 80%), but this difference was not significant ($p = 0.17$) at the 4-week rating. Among sequential treatments, first-pass herbicide had no effect on Palmer amaranth control at the 4-week rating ($p = 0.24$). Although the addition of 2,4-D choline to glufosinate was expected to improve control of large plants through systemic translocation, the second application itself appeared to accomplish the same function regardless of herbicide composition.

Application timing did not influence Palmer amaranth control at the 4-week rating in 2025 ($p = 0.45$). Control averaged 98% at 3 DAA, 97% at 10 DAA and 14 DAA, with no significant differences. The factorial analysis again detected no significant main effects or interactions among the herbicide and timing components ($p > 0.15$ for all terms).

2.3.4 Location-Specific Results

When data were pooled across years at Ashland Bottoms, treatment differences were evident. All 12 sequential treatments ranged from 96 to 99% control and were grouped together. The single application of G+ 2,4-D provided 88% control, which was intermediate, and the single application of G provided 80% control, which was less than all sequential programs (Table 2.4). The contrast between sequential and single applications was significant at Ashland Bottoms ($p < 0.05$), with sequential programs averaging 98% and single applications averaging 84%.

At Hays, Palmer amaranth control was uniformly high across all treatments. Sequential treatments ranged from 97 to 99%, and single applications of G and G+ 2,4-D Choline provided 95 and 98% control, respectively. No individual treatment comparisons were significant at Hays (Table 2.4). Despite this lack of separation among individual treatments, the overall contrast between sequential and single application strategies was still significant ($p < 0.05$), with sequential programs at 99% and single applications at 97%.

The contrasting patterns between locations explain the significant treatment-by-location interaction in the combined model. Ashland Bottoms differentiated treatments and revealed the advantage of sequential programs more clearly. Hays exhibited a ceiling effect in which nearly all treatments achieved near-complete control, compressing the differences that were visible at Ashland Bottoms.

2.3.5 Soybean Yield

Soybean yield varied substantially between locations in both years. At Ashland Bottoms, yield averaged 4,102 kg ha^{-1} in 2024 and 2,556 kg ha^{-1} in 2025. At Hays, yield averaged 404 kg ha^{-1} in 2024 and 1,412 kg ha^{-1} in 2025 (Table 2.5). In 2024, the treatment-by-location interaction for yield was significant ($p = 0.024$), and data were analyzed separately by location. At Ashland Bottoms, treatment did not affect yield ($p = 0.06$), and no individual treatment comparisons were significant (Table 2.5). Sequential and single application programs produced similar yield (4,109 versus 4,069 kg ha^{-1}; $p = 0.80$). At Hays, treatment did not affect yield ($p = 0.77$), and sequential and single application programs did not differ (403 versus 424 kg ha^{-1}; $p = 0.74$). Yields were uniformly low at Hays in 2024 regardless of treatment, likely due to late planting and limited precipitation during the growing season.

In 2025, the treatment-by-location interaction for yield was not significant ($p = 0.87$); however, data were examined by location to characterize site-specific responses. At Ashland Bottoms, treatment did not affect yield ($p = 0.65$), and sequential and single application programs did not differ (2,630 versus 2,327 kg ha^{-1}; $p = 0.32$). At Hays, treatment affected yield ($p = 0.01$; Table 2.5). G fb G at the 14 DAA interval produced the greatest yield at 1,742 kg ha^{-1}. A single application of G (1,150 kg ha^{-1}), G fb G + 2,4-D at 3 DAA (1,143 kg ha^{-1}), and a single application of G + 2,4-D (1,137 kg ha^{-1}) yielded least. Sequential application programs yielded 316 kg ha^{-1} more than single application programs at Hays in 2025 (1,459 versus 1,143 kg ha^{-1}; $p = 0.0006$).

2.3.6 Palmer Amaranth Biomass

Palmer amaranth aboveground biomass was collected in 2025 at both locations. Biomass data were not available for Hays in 2024, and only 6 observations were obtained at Ashland Bottoms in 2024, which were insufficient for statistical analysis and are reported in (Table 2.7) only.

In 2025, the treatment-by-location interaction for biomass was not significant ($p = 0.57$). At Ashland Bottoms, treatment did not affect biomass ($p = 0.67$). Six of the 12 sequential treatments produced zero Palmer amaranth biomass, and sequential and single application programs did not differ (14.4 versus 10.9 g m^{-2}; $p = 0.86$) (Table 2.6).

At Hays, individual treatment comparisons were not significant ($p = 0.18$; Table 2.6). However, when the 12 sequential treatments were pooled and compared against the two single-application treatments as a planned contrast, sequential programs produced less Palmer amaranth biomass (12.8 versus 45.6 g m^{-2}; $p = 0.001$). Single applications of G and G+ 2,4-D produced 53.4 and 37.8 g m^{-2} respectively but did not differ from each other ($p = 0.70$), while sequential programs ranged from 0.8 to 31.0 g m^{-2}. The biomass data at Hays in 2025 corroborate the visual control and yield results from that site-year: single-application treatments that provided lower Palmer amaranth control allowed greater weed biomass accumulation, which reduced soybean yield.

2.3.7 Economic Consideration

The cost of a second application must be weighed against the yield it protects. At Hays in 2025, sequential programs yielded 316 kg ha^{-1} more than single applications (1,459 vs. 1,143 kg ha^{-1}, $p = 0.0006$), and the biomass results confirmed that sequential programs accumulated less Palmer amaranth dry matter than single applications (12.8 vs. 45.6 g m^{-2},$p = 0.001$). At the 2025 U.S. season-average soybean price of $10.00 bu^{-1} (USDA-WASDE 2025), that yield advantage is worth approximately $116 ha^{-1}. Based on 2026 Kansas herbicide prices and custom application rates (K-State Research and Extension 2026; Kansas Department of Agriculture 2026), a single glufosinate (Liberty Ultra) application costs roughly $62 ha^{-1} and a sequential G fb G program costs $124 ha^{-1}. The incremental cost of the second pass is therefore $62 ha^{-1}, producing a net return of approximately $54 ha^{-1} and a 1.9:1 benefit-to-cost ratio. Adding 2,4-D choline to either pass increases program cost by roughly $22 ha^{-1} per application, but because herbicide composition did not significantly affect yield in this study, the added expense did not translate to additional revenue at any site-year. At Ashland Bottoms, sequential and single programs did not differ in yield in either year ($p = 0.80$ in 2024; $p = 0.32$ in 2025), and the second application would represent an added cost without a measurable same-season return. In fields where Palmer amaranth density is low enough that a single application achieves optimum control, the economic justification for the second pass shifts from immediate yield protection to long-term seedbank management, a cost that a single-season analysis does not capture.

Tables

Table 2.1 Herbicide treatments evaluated for control of Palmer amaranth (*Amaranthus palmeri*) in Enlist E3 soybean at Ashland Bottoms and Hays, KS, in 2024 and 2025.

Treatment	First-pass herbicide (Application A)	Second-pass herbicide (Application B)	Interval (DAA)	Rate (kg ha^{-1})
1	Nontreated			
2	G			0.59
3	G+2,4-D			0.59 + 0.53
4	G	G	3	0.59
5	G	G+2,4-D	3	0.59 / 0.59 + 0.53
6	G+2,4-D	G	3	0.59 + 0.53 / 0.59
7	G+2,4-D	G+2,4-D	3	0.59 + 0.53
8	G	G	10	0.59
9	G	G+2,4-D	10	0.59 / 0.59 + 0.53
10	G+2,4-D	G	10	0.59 + 0.53 / 0.59
11	G+2,4-D	G+2,4-D	10	0.59 + 0.53
12	G	G	14	0.59
13	G	G+2,4-D	14	0.59 / 0.59 + 0.53
14	G+2,4-D	G	14	0.59 + 0.53 / 0.59
15	G+2,4-D	G+2,4-D	14	0.59 + 0.53

Abbreviations: G, glufosinate (Liberty 280 SL in 2024; Liberty Ultra in 2025; BASF Corporation, Research Triangle Park, NC); 2,4-D, 2,4-D choline (Enlist One, Corteva Agriscience, Indianapolis, IN). Glufosinate applied at 0.59 kg ai ha^{-1}; 2,4-D choline applied at 0.53 kg ae ha^{-1}. Ammonium sulfate at 2.5% v/v was included with all herbicide treatments.. For sequential treatments with different herbicides in each pass, rates are listed as first-pass / second-pass.

Table 2.2 Palmer amaranth control at the 2nd pass, 2-week, and 4-week ratings as affected by herbicide treatment in 2024.

T.No	Herbicide	2nd pass[a]	2-week	4-week
2	G	45 a	91 b	96 ab
3	G+2,4-D	39 a	94 ab	94 b
4	G fb G (3 DAA)	51 a	99 a	97 ab
5	G fb G+2,4-D (3 DAA)	65 a	99 a	99 a
6	G+2,4-D fb G (3 DAA)	54 a	99 a	99 a
7	G+2,4-D fb G+2,4-D (3 DAA)	58 a	99 a	99 a
8	G fb G (10 DAA)	24 a	99 a	99 a
9	G fb G+2,4-D (10 DAA)	33 a	96 ab	99 a
10	G+2,4-D fb G (10 DAA)	40 a	99 a	99 a
11	G+2,4-D fb G+2,4-D (10 DAA)	39 a	99 a	99 a
12	G fb G (14 DAA)	25 a	94 ab	99 a
13	G fb G+2,4-D (14 DAA)	49 a	94 ab	99 a
14	G+2,4-D fb G (14 DAA)	41 a	98 ab	99 a
15	G+2,4-D fb G+2,4-D (14 DAA)	68 a	97 ab	99 a

Abbreviations: T.No, Treatment Number; G, glufosinate; 2,4-D, 2,4-D choline; fb, followed by; DAA, days after initial application.

Means within a column followed by the same letter are not significantly different ($\alpha = 0.05$). The 2-week and 4-week values are estimated marginal means averaged across locations.

[a] Second-pass ratings were collected at Ashland Bottoms only; Hays data were not available in 2024.

Table 2.1 Palmer amaranth control at the 2[nd] pass, 2-week, and 4-week ratings as affected by herbicide treatment pooled across Ashland Bottoms and Hays, KS, in 2025.

T.No	Treatment	2nd pass	2-week	4-week
2	G	51 a	87 b	80 b
3	G+2,4-D	55 a	91 ab	92 ab
4	G fb G (3 DAA)	57 a	97 ab	99 a
5	G fb G+2,4-D (3 DAA)	59 a	98 ab	99 a
6	G+2,4-D fb G (3 DAA)	56 a	97 ab	96 a
7	G+2,4-D fb G+2,4-D (3 DAA)	55 a	99 a	99 a
8	G fb G (10 DAA)	53 a	97 ab	97 a
9	G fb G+2,4-D (10 DAA)	54 a	96 ab	97 a
10	G+2,4-D fb G (10 DAA)	54 a	96 ab	96 a
11	G+2,4-D fb G+2,4-D (10 DAA)	58 a	99 a	99 a
12	G fb G (14 DAA)	54 a	91 ab	98 a
13	G fb G+2,4-D (14 DAA)	59 a	93 ab	99 a
14	G+2,4-D fb G (14 DAA)	59 a	91 ab	96 a
15	G+2,4-D fb G+2,4-D (14 DAA)	56 a	88 ab	96 a

Abbreviations: T.No, Treatment Number; G, glufosinate; 2,4-D, 2,4-D choline; fb, followed by; DAA, days after initial application.

Means within a column followed by the same letter are not significantly different (α = 0.05). Values are estimated marginal means averaged across locations.

Table 2.2 Palmer amaranth control at the 2-week and 4-week ratings by location, pooled across 2024 and 2025.

		Ashland Bottoms		Hays	
T.No	Treatment	2-week	4-week	2-week	4-week
2	G	81 d	80 b	97 a	95 a
3	G+2,4-D	86 cd	88 ab	99 a	98 a
4	G fb G (3 DAA)	97 abc	97 a	99 a	99 a
5	G fb G+2,4-D (3 DAA)	98 ab	99 a	99 a	99 a
6	G+2,4-D fb G (3 DAA)	97 abc	98 a	99 a	97 a
7	G+2,4-D fb G+2,4-D (3 DAA)	99 a	99 a	99 a	99 a
8	G fb G (10 DAA)	97 abc	97 a	99 a	99 a
9	G fb G+2,4-D (10 DAA)	95 abc	98 a	97 a	99 a
10	G+2,4-D fb G (10 DAA)	96 abc	96 a	99 a	99 a
11	G+2,4-D fb G+2,4-D (10 DAA)	99 a	99 a	99 a	99 a
12	G fb G (14 DAA)	86 cd	98 a	99 a	99 a
13	G fb G+2,4-D (14 DAA)	87 bcd	99 a	99 a	99 a
14	G+2,4-D fb G (14 DAA)	90 abcd	98 a	99 a	97 a
15	G+2,4-D fb G+2,4-D (14 DAA)	86 cd	97 a	99 a	98 a

Abbreviations: T.No, Treatment Number; G, glufosinate; 2,4-D, 2,4-D choline; fb, followed by; DAA, days after initial application.

Means within a column followed by the same letter are not significantly different (α = 0.05). Values are estimated marginal means averaged across years within each location.

Table 2.3 Soybean yield (kg ha^{-1}) as affected by herbicide treatment at Ashland Bottoms and Hays, KS, in 2024 and 2025.

		2024		2025	
T.No	Treatment	Ashland Bottoms	Hays	Ashland Bottoms	Hays
2	G	3,961 a	518 a	1890 a	1,150 b
3	G+2,4-D	4,224 a	330 a	2,771 a	1,137 b
4	G fb G (3 DAA)	4,109 a	437 a	2,616 a	1,459 ab
5	G fb G+2,4-D (3 DAA)	4,203 a	430 a	2,132 a	1,143 b
6	G+2,4-D fb G (3 DAA)	4,472 a	343 a	3,141 a	1,506 ab
7	G+2,4-D fb G+2,4-D (3 DAA)	4,344 a	370 a	2,482 a	1,480 ab
8	G fb G (10 DAA)	4,526 a	363 a	2,764 a	1,412 ab
9	G fb G+2,4-D (10 DAA)	3,961 a	437 a	3,100 a	1,406 ab
10	G+2,4-D fb G (10 DAA)	4,183 a	336 a	2,650 a	1,446 ab
11	G+2,4-D fb G+2,4-D (10 DAA)	3,901 a	363 a	2,226 a	1,506 ab
12	G fb G (14 DAA)	4,291 a	444 a	2,798 a	1,742 a
13	G fb G+2,4-D (14 DAA)	3,860 a	323 a	2,764 a	1,520 ab
14	G+2,4-D fb G (14 DAA)	3,940 a	484 a	2,650 a	1,533 ab
15	G+2,4-D fb G+2,4-D (14 DAA)	3,564 a	484 a	2,213 a	1,345 ab

Abbreviations: T.No, Treatment Number; G, glufosinate; 2,4-D, 2,4-D choline; fb, followed by; DAA, days after initial application.
Means within a column followed by the same letter are not significantly different ($\alpha = 0.05$).

Table 2.4 Palmer amaranth aboveground dry biomass (g m^{-2}) as affected by herbicide treatment at Ashland Bottoms and Hays, KS, in 2025.

T.No.	Treatment	Ashland Bottoms	Hays
2	G	14.7 a	53.4 a
3	G+2,4-D	7.2 a	37.8 a
4	G fb G (3 DAA)	7.0 a	18.4 a
5	G fb G+2,4-D (3 DAA)	0.0 a	26.6 a
6	G+2,4-D fb G (3 DAA)	0.0 a	31.0 a
7	G+2,4-D fb G+2,4-D (3 DAA)	0.0 a	8.3 a
8	G fb G (10 DAA)	81.3 a	23.2 a
9	G fb G+2,4-D (10 DAA)	39.4 a	4.1 a
10	G+2,4-D fb G (10 DAA)	31.4 a	8.7 a
11	G+2,4-D fb G+2,4-D (10 DAA)	1.0 a	0.8 a
12	G fb G (14 DAA)	0.0 a	3.3 a
13	G fb G+2,4-D (14 DAA)	13.2 a	2.9 a
14	G+2,4-D fb G (14 DAA)	0.0 a	21.8 a
15	G+2,4-D fb G+2,4-D (14 DAA)	0.0 a	4.5 a

Abbreviations: G, glufosinate; 2,4-D, 2,4-D choline; fb, followed by; DAA, days after initial application.

Means within a column followed by the same letter are not significantly different ($\alpha = 0.05$). Treatment did not significantly affect biomass at either location. However, the contrast of sequential versus single application programs was significant at Hays ($p = 0.001$).

Table 2.5 Palmer amaranth aboveground dry biomass (g m^{-2}) at Ashland Bottoms, KS, in 2024. Descriptive means only; insufficient observations for statistical analysis.

T.No	Treatment	n	Biomass (g m^{-2})
2	G	2	109.5
3	G+2,4-D	3	425.2
12	G fb G (14 DAA)	1	62.3

Abbreviations: T.No, Treatment Number; G, glufosinate; 2,4-D, 2,4-D choline; fb, followed by; DAA, days after initial application; n, number of observations.

Biomass data were not available for Hays in 2024. Only 6 total observations were collected across 3 treatments at Ashland Bottoms. No statistical comparisons were conducted.

Table 2.8. Environmental conditions at the time of herbicide applications at Ashland Bottoms (AB) and Hays (HA) in 2024 and 2025.

Site-year	Application	Air temp (°C)	RH (%)	Wind speed (km h^{-1})
AB 2024	1st POST	28	69	3.2
	2nd POST (3 DAA)	30	55	1.1
	2nd POST (10 DAA)	28	61	1.2
	2nd POST (14 DAA)	28	66	4.8
HA 2024	1st POST	26	64	1.6
	2nd POST (3 DAA)	32	32	1.6
	2nd POST (10 DAA)	31	45	16
	2nd POST (14 DAA)	26	46	4.5
AB 2025	1st POST	31	70	4.9
	2nd POST (3 DAA)	37	58	4.8
	2nd POST (10 DAA)	31	70	3.8
	2nd POST (14 DAA)	26	80	6.4
HA 2025	1st POST	28	52	8.6
	2nd POST (3 DAA)	29	75	13.8
	2nd POST (10 DAA)	28	60	11.2
	2nd POST (14 DAA)	40	64	19.3

Chapter 3 - Effect of Delta-T and Carrier Volume on glufosinate efficacy for Palmer amaranth (*Amaranthus palmeri*) control in soybean

Lalit Mohan[1], Koffi Badou-Jeremie Kouame[2], Elizabeth A. Yeager[3], and Sarah Ganske[1]*

Abstract

Glufosinate is one of the few postemergence herbicides that still provide effective control of multiple-resistant Palmer amaranth populations, but its efficacy is sensitive to environmental conditions at the time of application. Delta-T, defined as the difference between dry-bulb and wet-bulb temperature, integrates temperature and humidity into a single value describing the evaporative demand of the atmosphere during spraying. Field experiments were conducted at Manhattan, KS in 2024 and 2025 and at Hays, KS in 2025 to evaluate the effect of Delta-T on glufosinate efficacy for Palmer amaranth control in Enlist E3 soybean. Glufosinate (0.59 kg ai ha^{-1}) was applied alone or tank-mixed with 2,4-D choline (0.53 kg ae ha^{-1}) at two carrier volumes (93 and 187 L ha^{-1}) across multiple application dates within each site-year to capture a range of Delta-T conditions. The experiment was arranged as a randomized complete block design with four replications. At Manhattan 2024, where Delta-T ranged from 3.7 to 12.8 C, applications within the recommended 2 to 8 C range achieved 92% control with minimal variability, whereas applications above 8 C averaged 59% control with high plot-to-plot variation. For each 1 C increase in Delta-T, control decreased by 3.9 percentage points. Neither herbicide treatment nor carrier volume affected control at this site. At Hays 2025, where all applications fell within the 2 to 8 C range, mean control was only 68%, and both the addition of 2,4-D choline (73 versus

61%) and higher carrier volume (75 versus 59%) significantly improved control. Reduced efficacy at Hays was associated with low pre-application rainfall and reduced solar radiation rather than spray-day Delta-T. At Manhattan 2025, all applications achieved uniformly high control (87%) with no treatment effects. Delta-T is a useful field indicator for spray timing, but pre-application environmental conditions can override its predictive value under semi-arid conditions.

Nomenclature

Glufosinate; 2,4-D choline; Palmer amaranth, *Amaranthus palmeri* S. Watson; soybean, *Glycine max* (L.) Merr.; redroot pigweed, *Amaranthus retroflexus* L.; common waterhemp, *Amaranthus tuberculatus* (Moq.) Sauer; wild oat, *Avena fatua* L.; kochia, *Bassia scoparia* (L.) A.J. Scott; common lambsquarters, *Chenopodium album* L.; horseweed, *Erigeron canadensis* L.

Keywords: carrier volume; Delta-T; Enlist E3; glufosinate; Palmer amaranth; relative humidity; temperature; soybean; 2,4-D choline

3.1 Introduction

Glufosinate is a nonselective, primarily contact, post-emergence herbicide that inhibits glutamine synthetase (GS), a key enzyme in plant nitrogen metabolism (Takano and Dayan 2020). Inhibition of GS leads to rapid accumulation of ammonia and reactive oxygen species (ROS) in the presence of light, ultimately causing membrane destruction and cell death (Takano et al. 2019). With the widespread evolution of resistance to glyphosate, acetolactate synthase (ALS) inhibitors, and protoporphyrinogen oxidase (PPO) inhibitors in Palmer amaranth populations across the southern and central United States (Heap 2026), glufosinate has become one of the most important post-emergence herbicides remaining for Palmer amaranth management in soybean production systems. However, glufosinate efficacy is highly sensitive to environmental conditions at the time of application, and inconsistent weed control under suboptimal weather remains a persistent challenge for producers. (Coetzer et al. 2001; Landau et al. 2025).

The environmental sensitivity of glufosinate has been studied extensively under controlled conditions. Coetzer et al. (2001), working at Kansas State University, demonstrated that relative humidity (RH) had a greater effect on glufosinate toxicity to Palmer amaranth, redroot pigweed, and common waterhemp than did temperature. At 90% RH, all rates of glufosinate caused severe leaf wilting within one day after treatment, whereas at 35% RH, comparable symptoms were delayed by two to three days and control 14 days after treatment was reduced by 30 to 50 percentage points depending on species and rate. Importantly, the mechanism was not a reduction in absorption but rather a reduction in translocation: at 90% RH, up to 31% of absorbed glufosinate translocated out of the treated leaf, compared with less than 6% at 35% RH. Ramsey et al. (2002) extended these findings in wild oat, showing that even 30 minutes of exposure to high RH (>95%)

before and after spraying was sufficient to increase glufosinate efficacy to levels comparable with continuous high-humidity exposure.

Light and temperature also influence glufosinate performance. Time-of-day effects on glufosinate efficacy were first documented in velvetleaf by Sellers et al. (2003), who showed that reduced efficacy at sunset applications could not be explained by leaf angle alone, pointing toward an underlying physiological mechanism. Sellers et al. (2004) subsequently demonstrated that glutamine synthetase (GS) activity diminished rapidly during the light period following glufosinate treatment but remained high during the dark period, while absorption and translocation were not associated with the reduced efficacy. Takano and Dayan (2021) later investigated the biochemical basis for the time-of-day effect on glufosinate efficacy in Palmer amaranth and found that GS gene expression and protein abundance were greater in the light than in the dark. Mid-day application of glufosinate inhibited GS activity by more than 95% within two hours and maintained that suppression permanently, whereas dusk application achieved only 82% inhibition, and plants recovered full GS activity within days through rapid enzyme recovery. These findings explain why glufosinate performs best when applied under full sunlight at midday, but they also highlight a practical tension: midday conditions in summer are typically the hottest and driest part of the day, precisely when RH is lowest, and spray droplets evaporate most rapidly. Montgomery et al. (2017) confirmed this pattern in field trials on horseweed, reporting that glufosinate applied at midday provided 92% control at 28 DAT, compared with 63% from sunrise applications and 79% from sunset applications. Stopps et al. (2013) similarly reported species-specific time-of-day effects across multiple postemergence herbicides in Ontario soybean, with weed control generally reduced when applications were made at 6:00 AM, 9:00 PM, or midnight.

Recent work has further shown that environmental effects on glufosinate efficacy extend beyond conditions present only at the time of application. Landau et al. (2025) provided the broadest retrospective analysis of weather effects on glufosinate efficacy currently available, using a database of more than 10,000 North American herbicide evaluation trials. Their analysis indicated that relative humidity ≤70% on the day of application reduced the probability of successful control across all species examined; solar radiation ≤17 MJ m^{-2} d^{-1} reduced control of Ipomoea spp., while ≤23 MJ m^{-2} d^{-1} reduced control of giant foxtail; total rainfall ≤ 20 mm, collectively in the 5 days before application was detrimental to waterhemp and giant foxtail control; and average air temperature of ≤ 25 C in 5 days after application reduced successful control of all species. Notably, Landau et al. identified pre-application rainfall as an important predictor, indicating that environmental conditions in the days before spraying may influence plant surface and physiological traits relevant to foliar glufosinate uptake, in addition to spray-day weather. Similarly, Desai et al. (2025) demonstrated that environmental mediation of glufosinate efficacy extends beyond application-day conditions, showing in controlled glasshouse experiments that the duration of post-application elevated RH required for effective control was species-specific: kochia achieved complete control after only brief exposure to elevated RH (≥60%), whereas common lambsquarters remained incompletely controlled even after prolonged exposure. Collectively, these findings indicate that glufosinate efficacy can be influenced by a temporal window of environmental conditions spanning the period before, during and after application.

Although previous research has demonstrated that glufosinate efficacy responds to multiple environmental variables, many of these variables are difficult to integrate into real-time field decisions. Applicators must make spray decisions under field conditions using measurements that are immediately available at the time of application. Among the environmental factors known to affect glufosinate activity, air temperature and humidity at the time of spraying are readily measurable in the field and directly influence droplet behavior, drying time, and plant surface conditions. Therefore, among the environmental factors affecting herbicide performance, temperature and humidity at the time of application provide the most practical basis for a field-use decision tool. A widely used applicator practice is the "150 rule," in which the sum of air temperature (°F) and relative humidity (%) is targeted at or above 150 as a simple field indicator of favorable spray conditions for glufosinate. The rule reflects an important principle, that warm and humid conditions support glufosinate activity, and a more quantitative version of this same principle is captured by integrated measures of atmospheric evaporative demand.

Delta-T (ΔT), defined as the difference between the dry-bulb air temperature and the wet-bulb or dew point temperature, integrates application-time temperature and humidity into a single value describing the evaporative demand of the atmosphere during spraying and has been widely adopted in Australian spray application guidelines through the Grains Research and Development Corporation. When Delta-T is low (<2 °C), the air is near saturation and spray conditions are often unfavorable because of increased drift risk and prolonged droplet persistence. When Delta-T falls within the recommended range of 2 to 8 °C, conditions generally balance droplet survival. Values between 8 and 10 °C are considered a caution zone, indicating increasingly evaporative conditions that may reduce application quality. When Delta-T exceeds 10°C, atmospheric conditions are trending toward warm and moisture-deficient, accelerating droplet evaporation and potentially reducing herbicide performance (GRDC 2025; Sprayers 101).

Conceptually, Delta-T provides a practical framework for integrating the temperature- and humidity-related conditions previously shown to influence glufosinate activity. However, the Delta-T thresholds used in Australian spray application guidelines originate primarily from extension and application guidance rather than from peer-reviewed, replicated field experiments. Furthermore, no peer-reviewed field study has tested whether application-time Delta-T predicts glufosinate efficacy on Palmer amaranth under North American field conditions. If validated, Delta-T could provide applicators with a simple, field-measurable indicator of application-time evaporative demand that complements broader knowledge of the environmental factors affecting glufosinate performance.

In addition to application-time environment, herbicide tank-mixture and spray carrier volume may influence glufosinate performance. The Enlist E3 soybean platform provides growers with the option to tank-mix glufosinate with 2,4-D choline, adding a systemic synthetic auxin herbicide to the contact activity of glufosinate. Craigmyle et al. (2013) demonstrated that mixtures of glufosinate and 2,4-D controlled common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] more effectively than either herbicide alone, with the magnitude of improvement increasing as weed height increased. However, whether this tank-mix benefit interacts with spray-time environmental conditions, specifically whether 2,4-D choline compensates for reduced glufosinate efficacy under suboptimal conditions has not been examined.

Carrier volume may also influence herbicide performance under suboptimal environmental conditions by affecting spray coverage and deposition on the target surface. Greater carrier volumes increase spray coverage and may partially compensate for rapid droplet evaporation under suboptimal conditions by delivering more solution to the target. Label directions for glufosinate specify a minimum carrier volume of 140 L ha^{-1} for ground application and recommend increasing spray volume to 187 L ha^{-1} when dense weed canopies are present to improve spray coverage. Whether increasing carrier volume from 93 L ha^{-1} to 187 L ha^{-1} mitigates efficacy losses under unfavorable conditions like drought stress, low solar radiation, temperature and humidity has practical relevance for applicators.

To test these interactions, the objectives of this study were to (1) evaluate the relationship between Delta-T at the time of glufosinate application and the level of Palmer amaranth control achieved under field conditions, (2) determine whether tank-mixing 2,4-D choline with glufosinate mitigates reduced efficacy under suboptimal application conditions, and (3) assess whether carrier volume influences glufosinate efficacy.

3.2 Materials and Methods

Field experiments were conducted at the Ashland Bottoms Research Farm near Manhattan, in 2024 (39°07'28.7"N 96°36'26.7"W) and 2025 (39°07'02.2"N 96°38'14.9"W) and the Western Kansas Agricultural Research Center near Hays, KS in 2025 (38°51'10.1"N 99°19'37.4"W). The soil at Ashland Bottoms was Reading silt loam with pH 6.5 and 2.6% organic matter. The soil at Hays was Crete silty clay loam with pH 7.9 and 3.2% organic matter. These two locations were selected to represent the environmental gradient across Kansas soybean production: Manhattan receives approximately 880 mm of annual precipitation and typifies the sub-humid eastern Kansas environment, while Hays receives approximately 621 mm annually and represents the semi-arid conditions of western Kansas. Both sites have history of established Palmer amaranth populations.

Enlist E3 soybean varieties were planted and differed by site-year. P38Z63E was planted at Manhattan in 2024 and at Hays in 2025, whereas B392EE was planted at Manhattan in 2025 in 76-cm rows at 5cm depth. The trial was planted in early July 2024 at Manhattan, and on 13th of May in 2025 with a seeding rate of 296,526 hectare^{-1}. In Hays 2025, soybean was planted on June

1 with a seeding rate of 385,484 hectare^{-1} and in 2024 on July 10 with a seeding rate of 387,700 ha^{-1}. No pre-emergence herbicide was applied in order to allow natural Palmer amaranth establishment across all plots. The experiment was arranged as a randomized complete block design (RCBD) with four replications at each location-year. Individual plots measured 3 × 9.1 m.

3.2.1 Treatments

Treatments were arranged as a complete factorial of two herbicide programs, two carrier volumes, and four application times (each corresponding to a different Delta-T condition). Glufosinate (Liberty 280 SL in 2024, Liberty Ultra in 2025; BASF Corporation, Research Triangle Park, NC) was applied at 0.59 kg ai ha^{-1} either alone or tank-mixed with 2,4-D choline (Enlist One; Corteva Agriscience, Indianapolis, IN) at 0.53 kg ae ha^{-1}, and each herbicide treatment was applied at both 93 and 187 L ha^{-1}. Ammonium sulfate at 2.5% v/v was included with all treatments. A nontreated control was included for reference (Table 3.1).

3.2.2 Herbicide Application and Environmental Measurements

All treatments were applied using a CO2-pressurized backpack sprayer operated at a speed of 3 km h^{-1}. Glufosinate-only treatments were applied with TeeJet Turbo TwinJet TTJ11002 nozzles, and treatments that included 2,4-D choline were applied with TeeJet Air Induction Extended Range AIXR11002 nozzles (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL) to comply with label requirements for drift reduction. In 2025, the corresponding 11003 nozzle models were used, with TTJ11003 nozzles for glufosinate-only treatments and AIXR11003 nozzles for treatments containing 2,4-D choline. Applications were made 2 hours after sunrise and 3 hours before sunset to comply with glufosinate label guidelines regarding time of day. Applications were made when Palmer amaranth had reached at least 20 cm to represent late-season escape population.

Air temperature, relative humidity, and Delta-T were recorded at the time of application using a Kestrel 5500AG Weather Meter (Kestrel Instruments, Boothwyn, PA) (Table 3.7).

3.2.3 Data Collection

Palmer amaranth control was visually assessed at 7 and 21 days after treatment (DAT) on a scale of 0 to 100%, where 0 indicated no visible effect and 100 indicated complete plant death, relative to the nontreated control. The 7 DAT rating was recorded to assess initial herbicide activity. The 21 DAT rating was used as the primary response variable for all analyses as it captures the final treatment effect after initial symptom expression and potential regrowth.

Palmer amaranth biomass was collected before each application and 3 weeks after the last application in two 1m^2 quadrats plot^{-1} in paper bags, dried at 55 °C until constant weight and dry weights recorded. Soybean was harvested from the center rows of each plot, and grain yield was adjusted to 13% moisture. Yield data were not available for 2024.

3.2.4 Statistical Analysis

All data were analyzed in R version 4.4.1 (R Core Team 2024) within the RStudio environment (version 2024.09.0+375) using linear mixed-effects models fit with the lmer function from the lme4 package (Bates et al. 2015) and the lmerTest package (Kuznetsova et al. 2017) for Satterthwaite-approximated denominator degrees of freedom. Replication was included as a random effect in each site-year model. Type III analysis of variance was conducted using the anova function from the lmerTest package to test the significance of herbicide treatment, carrier volume, Delta-T, and their interactions.

A combined analysis was first conducted to test whether treatment effects differed across site-years. The model included herbicide treatment, carrier volume, Delta-T, site-year, and the two-way interactions of each treatment factor with site-year as fixed effects, and replication nested within site-year as a random effect. Because the site-year by Delta-T interaction was significant, subsequent analyses were conducted separately by site-year. Within each site-year, a full factorial model including all two-way and three-way interactions among Delta-T, herbicide treatment, and carrier volume was fit first. Because no interactions were significant at any site-year ($p > 0.07$ for all interaction terms), the additive model was used for final inference.

The relationship between Delta-T and Palmer amaranth control was further assessed using both categorical and continuous approaches depending on the site-year. For the categorical analysis, Delta-T at the time of application was classified into optimal (2 to 8 °C) and high (>8 °C) categories and estimated marginal means for each category were compared using the emmeans package (Lenth 2023) with pairwise contrasts evaluated at $\alpha = 0.05$. For the continuous analysis, a separate linear regression was fit for each site-year to model Palmer amaranth control at 7 and 21 DAT as a function of Delta-T. Quadratic and cubic models were also fit for each site-year and compared to the linear model using nested F-tests. Forward and backward stepwise regression was used to rank the environmental variables by their contribution to Palmer amaranth control, with Delta-T, solar radiation, five-day cumulative precipitation, average wind speed, herbicide treatment, and carrier volume as predictors. Each environmental variable was recorded once per application date and therefore took the same value for all plots treated on that date.

Compact letter displays for mean separation were generated using the multcomp package (Hothorn et al. 2008); means not sharing a common letter differ significantly ($p \leq 0.05$).

Visual control data were also analyzed following arcsine square root transformation; all primary conclusions were unchanged, and untransformed results are presented for ease of interpretation as the F-test in ANOVA is robust to departures from normality, particularly with balanced designs (Blanca et al. 2017).

Palmer amaranth biomass and soybean yield were analyzed using the same mixed-effects approach as visual control. Biomass was analyzed as the change from pre-application to post-application to account for differences in initial weed size among plots sprayed on different dates. Yield data were available for Hays 2025 and Manhattan 2025 only, a combined analysis across the two site-years was conducted first to test for site-year interactions with treatment factors, with replication nested within site-year as a random effect. If interactions were significant, yield was analyzed separately by site-year. Within each site-year, a full factorial model was fit first; treatment interactions that were significant were retained in the final model.

3.3 Results and Discussion

3.3.1 Combined Analysis

The combined analysis of variance detected a site-year by Delta-T interaction for Palmer amaranth control at both 7 DAT ($p = 0.001$) and 21 DAT ($p < 0.001$), indicating that the relationship between Delta-T and weed control differed among site-years. The interactions of site-year with herbicide treatment and site-year with carrier volume were not significant at either rating ($p \geq 0.12$ for all). Because Delta-T interacted with site-year, all subsequent analyses were conducted separately by site-year. The three site-years differed substantially in their Delta-T range: Manhattan 2024 spanned 3.7 to 12.8 C, covering both optimal and high conditions, whereas Hays 2025 (3.5 to 7.9 C) and Manhattan 2025 (2.5 to 7.4 C) were entirely within the optimal range. Within each site-year, a full factorial model including all two-way and three-way interactions among Delta-T, herbicide treatment, and carrier volume was fit first. Because no interactions were significant at any site-year ($p > 0.07$ for all interaction terms), the additive model was used for final inference.

3.3.2 Manhattan 2024

Manhattan 2024 was the only site-year in which Delta-T at the time of application spanned both optimal and high conditions, ranging from 3.7 to 12.8 C across four application dates. Delta-T was the only factor that affected Palmer amaranth control at 21 DAT.

The Delta-T effect was evident at 7 DAT, with control declining at a slope of -3.3 percentage points per degree Celsius. Herbicide treatment and carrier volume did not significantly affect control at 7 DAT (Table 3.2). The same pattern persisted at 21 DAT. Delta-T was the only factor that affected Palmer amaranth control (Table 3.2). Estimated marginal means for the main effects were 77.5% for glufosinate plus 2,4-D choline and 73.3% for glufosinate alone, and 76.9% for 187 L ha^{-1} and 73.9% for 93 L ha^{-1} (Table 3.3). These results provide field-level validation that the 2 to 8 °C Delta-T range recommended in Australian spray application guidelines (GRDC 2025) has predictive value for glufosinate efficacy on Palmer amaranth under North American conditions. Applications made within this range achieved 92% control with minimal variability, whereas applications at Delta-T above 8 °C averaged 33 percentage points lower with substantially greater plot-to-plot variation.

In regression, for each 1 °C increase in Delta-T, control decreased by 3.9 percentage points (R^2 = 0.22). When analyzed separately by herbicide treatment, the slope was similar for glufosinate alone (slope = -4.2, p = 0.007, R^2 = 0.22) and glufosinate plus 2,4-D choline (slope = -3.6, p = 0.009, R^2= 0.22), indicating that both treatments declined at comparable rates as Delta-T increased.

When Delta-T was classified categorically, applications made under optimal conditions (2 to 8 °C; n = 30) achieved 92.3% control (SD = 4.1), whereas applications made under high Delta-T conditions (>8 °C; n = 32) achieved 59.4% control (SD = 37.3). Beyond the difference in mean control, the variability of outcomes increased substantially under high Delta-T: the standard deviation increased from 4.1 under optimal conditions to 37.3 under high Delta-T, indicating that applications made under high evaporative demand produced not only lower average control but also highly unpredictable outcomes.

3.3.3 Hays 2025

At Hays 2025, Delta-T at the time of application ranged from 3.5 to 7.9 °C across application dates (July 1, 2, and 4), all within the optimal range as defined by Australian spray application guidelines. Mean Palmer amaranth control at 21 DAT was 67.5%, compared to 92.3% achieved under comparable Delta-T conditions at Manhattan 2024.

At 7 DAT, control across all factors was 88.4%, and neither Delta-T nor herbicide treatment affected control. Carrier volume was the only significant factor at 7 DAT (Table 3.2), but the consistently high mean control across all application dates indicates that initial herbicide symptom expression was uniformly strong regardless of application timing.

At 21 DAT, Delta-T became significant in the additive model (Table 3.2), but unlike Manhattan 2024, the slope was positive (+10.6 percentage points per degree Celsius). Even though all applications occurred within the optimal Delta-T range, the positive coefficient does not indicate that higher Delta-T improved herbicide performance. Rather, control differences across dates reflect environmental factors beyond application-time Delta-T.

The divergence between the 7 DAT and 21 DAT patterns suggests that the reduced efficacy observed at 21 DAT on certain application dates was not due to immediate application failure but rather to incomplete absorption or translocation that became apparent as surviving plants recovered and resumed growth between 7 and 21 DAT.

For instance, July 4 applications (Delta-T = 3.5 and 5.4 °C) produced the lowest 21 DAT control (43% and 57%), while the July 1 and 2 applications (Delta-T = 7.9 and 7.0 °C) achieved 85% and 86% control, respectively.Kansas Mesonet weather data (Table 3.4) indicate that the reduced efficacy on July 4 was primarily associated with three conditions, two of which identified by Landau et al. (2025) as detrimental to glufosinate performance. First, solar radiation on July 4 was 16.4 MJ m^{-2} d^{-1}, below the 23 MJ m^{-2} d^{-1} threshold above which he reported increased probability of successful control of weed species. Because glufosinate efficacy depends on light-driven generation of reactive oxygen species through inhibition of glutamine synthetase during photosynthesis (Takano et al. 2019), reduced solar radiation directly limits the herbicidal mechanism. Second, cumulative precipitation of 5 days before the July 4 application was 1.78 mm, well below the 20 mm threshold identified by Landau et al. as favorable for successful control of pigweed species. Third, 0.51 mm of precipitation was recorded at Hays on July 4, which may have physically removed a portion of the applied herbicide from the leaf surface before complete absorption occurred.

Notably, the July 4 application had the highest relative humidity (73.8%) and lowest air temperature (30.4 °C) of all spray dates at Hays and was the only application date on which RH exceeded Landau et al.'s 70% threshold. Despite these favorable spray-day conditions, control was the lowest observed at this site. This result illustrates a central limitation of application-time metrics: they capture atmospheric evaporative demand at the moment of spraying but do not account for pre-application environmental history that may alter the target plant's susceptibility to foliar-applied herbicides.

The contrast between Hays and the Manhattan in 2025 highlights this limitation directly. Solar radiation was below the threshold reported by Landau et al. (2025) at both sites on those dates

(16.4 and 9.6 MJ m^{-2} d^{-1}, respectively). Despite the fact, control averaged 85% at Manhattan compared with 43 to 57% at Hays. But in the 30 days preceding the first application, Hays received 52 mm of total precipitation compared with 133 mm at Manhattan. These results suggest that the reduced control at Hays was not driven by spray-day Delta-T, which remained within the optimal range at both sites, but by a combination of higher wind speeds at application, which accelerate droplet evaporation and reduce foliar deposition, and a chronic pre-application moisture deficit that likely reduced plant susceptibility to foliar herbicide uptake. (Table 3.7)

Unlike the Manhattan site-years, both herbicide treatment and carrier volume affected Palmer amaranth control at Hays 2025 at 21 DAT (Table 3.2). The addition of 2,4-D choline to glufosinate increased control from 61% to 73% and increasing carrier volume from 93 to 187 L ha^{-1} increased control from 59% to 75% (Table 3.3). These results indicate that under stressful environmental conditions, treatment factors that had no detectable effect at the other site-years became important determinants of weed control. When environmental conditions favor herbicide performance, differences in tank-mix partners and application parameters may be masked by the high baseline efficacy of the primary herbicide. However, when conditions compromise herbicide absorption, translocation or plant susceptibility, as occurred at Hays, optimizing secondary factors such as herbicide combinations and carrier volume becomes critical for achieving acceptable control. The addition of 2,4-D choline likely compensated for reduced glufosinate efficacy by providing systemic auxin activity when contact herbicide performance alone was insufficient, while higher carrier volumes improved spray coverage and deposition when plant surfaces were less receptive to herbicide uptake. The pattern at Hays parallels findings by Ogden (2020), who reported that Palmer amaranth control with glufosinate alone was often insufficient and that adding 2,4-D choline to the system improved outcomes, particularly when targeting larger or more stressed plants.

3.3.4 Manhattan 2025

At Manhattan 2025, Delta-T ranged from 2.5 to 7.4 °C across four application dates, entirely within the optimal range. At 7 DAT, no treatment factors significantly affected Palmer amaranth control (Table 3.2). At 21 DAT, mean control was 86.6% (SD = 8.9), the greatest and least variable of the three site-years. No treatment factor was significant at 21 DAT (Table 3.2).

The regression model as a whole explained less than 2% of the variation in control ($R^2 < 0.01$). These results indicate that under consistently favorable environmental conditions, high levels of Palmer amaranth control were achieved regardless of herbicide treatment or carrier volume. The absence of any treatment effect at Manhattan 2025 carries practical significance. When environmental conditions throughout the application window are consistently favorable, optimizing herbicide mixture and carrier volume provided no measurable benefit. This finding suggests that the treatment effects observed at Hays 2025 were not intrinsic properties of the herbicide treatments but rather emerged under environmental stress. Applicators spraying under favorable conditions can expect high levels of Palmer amaranth control from glufosinate alone at standard carrier volumes, whereas applicators operating in semi-arid environments or during periods of drought should prioritize higher carrier volumes and/or the inclusion of a systemic tank-mix partner.

3.3.5 Palmer amaranth Biomass

Post-application Palmer amaranth biomass showed contrasting patterns across site-years. At Manhattan 2024, mean biomass increased from 51.4 g at pre-application to 93.4 g at 21 DAT despite high visual control across most plots (Table 3.5).

A positive correlation between visual control and post-application biomass was observed at this site-year ($r = 0.52$, $p < 0.001$). Plots providing excellent control (91 to 100%) averaged 125 g of post-application biomass compared with 44 g in plots providing poor control (0 to 30%). This pattern is consistent with density-dependent compensatory growth: in plots where the herbicide killed the majority of Palmer amaranth, the few surviving individuals faced reduced intraspecific competition for light, water, and nutrients, allowing them to accumulate substantially more biomass per plant than individuals in dense, poorly controlled stands. Palmer amaranth individual plant biomass increases with decreasing population density (Bensch et al. 2003), and the species rapid growth rate of 0.18 to 0.21 cm per growing degree day (Horak and Loughin 2000) enables surviving plants to exploit released resources quickly. None of the factors significantly affected biomass change at Manhattan 2024 (Delta-T $p = 0.17$, herbicide $p = 0.97$, carrier volume $p = 0.25$), consistent with the visual control results at this site-year.

At Manhattan 2025, mean biomass decreased from 57.3 g to 27.5 g, and no treatment factors significantly affected biomass change (Delta-T $p = 0.70$, herbicide $p = 0.33$, carrier volume $p = 0.41$), consistent with the uniformly high visual control observed at this site-year (Table 3.5).

At Hays 2025, mean biomass decreased from 77.9 g to 44.6 g. Herbicide treatment significantly affected the change in biomass: the addition of 2,4-D choline to glufosinate produced a mean biomass reduction of 46.8 g compared with 22.4 g for glufosinate alone ($p = 0.01$). Carrier volume had a marginal effect, with the higher volume producing a mean reduction of 42.8 g compared with 24.9 g at the lower volume ($p = 0.07$). Delta-T was not associated with biomass change at this site ($p = 0.25$) (Table 3.5).

The biomass change results at Hays 2025 are consistent with the visual control findings, where both 2,4-D choline addition and higher carrier volume improved control. This agreement between independent response variables strengthens the conclusion that both treatment factors contributed meaningfully to weed control under the chronic drought and reduced solar radiation conditions at this site, even though spray-day Delta-T remained within the optimal range.

3.3.6 Yield

Soybean yield differed substantially between locations, averaging 1,157 kg ha^{-1} at Hays 2025 and 2,441 kg ha^{-1} at Manhattan 2025. The combined analysis confirmed a strong site-year effect ($p < 0.001$), while no treatment factor interactions with site-year were significant. Yield was analyzed separately by site-year to characterize location-specific responses.

At Hays, the full factorial model identified a significant herbicide × carrier volume interaction for yield ($p = 0.027$). Three of the four herbicide × carrier volume combinations produced similar yields (1,083 to 1,143 kg ha^{-1}). The exception was glufosinate + 2,4-D choline applied at 187 L ha^{-1}, which yielded 1,278 kg ha^{-1} and was the only combination that differed from the lowest-yielding treatment (Table 3.6). This interaction suggests that the yield benefit of adding 2,4-D choline was realized only at the higher carrier volume.

At Manhattan 2025, none of the treatment factors affected yield (Delta-T $p = 0.94$, herbicide $p = 0.50$, carrier volume $p = 0.66$), consistent with the uniformly high visual control at this site. Yield averaged 2,401 kg ha^{-1} for glufosinate alone and 2,488 kg ha^{-1} for glufosinate + 2,4-D choline.

3.3.7 Delta-T Compared to the 150 Rule

To evaluate Delta-T against the 150 rule as a spray-day decision tool, spray-day conditions at each application were classified by both Delta-T (optimal: 2 to 8 °C) and the 150 rule (T °F + RH % ≥ 150) (Tables 3.8, 3.9, 3.10). Of the 12 applications across three site-years, seven met both criteria, three met the Delta-T criterion but not the 150 rule, and two met neither. No application met the 150 rule while falling outside the optimal Delta-T range.

When both metrics indicated favorable conditions, Palmer amaranth control ranged from 42.8 to 94.0%. The wide range was driven by the Hays 2025 July 4 application, which met both criteria (T + RH = 154.8; Delta-T = 3.5 °C) yet produced the lowest control in the study. Conversely, the Manhattan 2024 September 3 application met neither criterion (T + RH = 120; Delta-T = 12.75 °C) yet achieved 89.1% control. These results indicate that neither Delta-T nor the 150 rule, alone or in combination, reliably predicted glufosinate efficacy across the conditions encountered in this study.

The inability of either metric to explain the Hays 2025 outcome is consistent with the finding that pre-application plant condition, rather than spray-day atmospheric variables, was the primary driver of the site-year differences observed. Both Delta-T and the 150-rule capture atmospheric evaporative demand at the moment of spraying, but neither accounts for cumulative environmental history that determines plant susceptibility to foliar herbicide uptake.

The limited number of application environments in this study restricts the ability to rigorously compare the predictive accuracy of Delta-T and the 150 rule. A targeted comparison would require repeated applications across a wider range of Delta-T and T + RH combinations, including conditions where the two metrics disagree, across multiple locations and years. Such trials would clarify whether Delta-T offers meaningful improvement over the 150 rule as a spray-day decision tool for glufosinate.

3.3.8 Environmental Variable Analysis

The linear regressions used to describe the Delta-T relationship were checked against quadratic and cubic models at each site-year. The quadratic term was not significant at any site-year (p = 0.44, 0.86, and 0.83 for Manhattan 2024, Hays 2025, and Manhattan 2025), and the linear model was retained. The cubic term was significant at Manhattan 2024 and Manhattan 2025, but this reflected the small number of distinct Delta-T values at each site rather than a true curve.

Forward and backward stepwise regression was used to compare Delta-T to the other environmental variables across all site-years. Both procedures selected the same model, which retained solar radiation, five-day precipitation, herbicide treatment, and carrier volume, and dropped Delta-T and wind speed.

Solar radiation explained 12.2% of the variation in control, and five-day precipitation explained an additional 29.4%, for a combined 41.6%. The application dates with the lowest control had low solar radiation and little pre-application rainfall, while the dates with the highest control had more of both. Together, solar radiation and pre-application precipitation were the environmental variables most strongly associated with glufosinate efficacy, underscoring that pre-application growing conditions shape how well the herbicide performs.

3.3.9 Economic Considerations

The relevant economic question for applicators adjusting carrier volume and tank-mix composition is whether these modifications pay for themselves when environmental conditions compromise glufosinate performance. At Hays in 2025, the herbicide by carrier volume interaction ($p = 0.027$) revealed that glufosinate plus 2,4-D choline applied at 187 L ha^{-1} yielded 1,278 kg ha^{-1} whereas glufosinate alone at 93.5 L ha^{-1} yielded 1,110 kg ha^{-1} and glufosinate plus 2,4-D choline at 93.5 L ha^{-1} yielded 1,083 kg ha^{-1} .Neither adding 2,4-D choline at the lower volume nor increasing volume alone produced yield benefit; the advantage required both adjustments together. At the 2025 U.S. season-average soybean price of \$10.00 bu^{-1} (USDA-WASDE 2025), the 168 kg ha^{-1} yield difference between glufosinate alone at 93.5 L ha^{-1} and glufosinate plus 2,4-D choline at 187 L ha⁻

^{1} is worth approximately \$62 ha^{-1}. The cost of including 2,4-D choline adds \$22 ha^{-1} (K-State Research and Extension 2026), and doubling carrier volume adds only \$4 ha^{-1} in adjuvant because the herbicide rate and custom application charge (KDA 2026) remain unchanged regardless of spray volume. The combined adjustment costs roughly \$26 ha^{-1} and returned approximately \$62 ha^{-1} in yield protection, a 2.4:1 benefit-to-cost ratio. At Manhattan in 2025, where environmental conditions were consistently favorable, neither carrier volume nor herbicide composition affected yield, and the same \$26 ha^{-1} would represent cost without return. The economic value of these adjustments is therefore conditional on environment: under drought stress or low solar radiation they function as low-cost insurance that more than recovers its expense, while under favorable conditions glufosinate alone at standard volume achieves equivalent outcomes at lower input cost.

Tables

Table 3.1. Treatment structure for the experiment conducted at Manhattan and Hays, KS in 2024 and 2025.

Treatment	Herbicide treatment	Rate	Carrier volume
1	Nontreated control	-	-
2	G	0.59 kg ai ha^{-1}	93 L ha^{-1}
3	G	0.59 kg ai ha^{-1}	187 L ha^{-1}
4	G + 2,4-D	0.59 kg ai ha^{-1} + 0.53 kg ae ha^{-1}	93 L ha^{-1}
5	G + 2,4-D	0.59 kg ai ha^{-1} + 0.53 kg ae ha^{-1}	187 L ha^{-1}

Abbreviations: G, glufosinate; 2,4-D, 2,4-D choline; ai, active ingredient; ae, acid equivalent.
Ammonium sulfate at 2.5% v/v was included with all herbicide treatments.

Table 3.2**.** ANOVA p-values for the effects of Delta-T, herbicide treatment, and carrier volume on Palmer amaranth control at 7 DAT and 21 DAT at three site-years.

Site-year	Factor	7 DAT	21 DAT
Manhattan 2024	Delta-T	< 0.001***	< 0.001***
	Herbicide	0.95	0.57
	Carrier volume	0.71	0.68
Hays 2025	Delta-T	0.60	< 0.001***
	Herbicide	0.06	0.007**
	Carrier volume	0.007**	< 0.001***
Manhattan 2025	Delta-T	0.75	0.71
	Herbicide	0.43	0.54
	Carrier volume	0.35	0.75

Abbreviation: DAT, days after treatment. Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Table 3.3. Estimated marginal means and compact letter displays for Palmer amaranth control (%) at 21 DAT by herbicide treatment and carrier volume at each site-year.

Factor	Level	Manhattan 2024	Hays 2025	Manhattan 2025
Herbicide	Glufosinate	73.3 a	61 b	85.9 a
	Glufosinate + 2,4-D	77.5 a	73 a	87.3 a
Carrier volume	93 L ha^{-1}	73.9 a	59.4 b	86.2 a
	187 L ha^{-1}	76.9 a	74.6 a	87.0 a

Abbreviation: DAT, days after treatment; 2,4-D, 2,4-D choline. Means within a factor and site-year followed by the same letter are not significantly different (α = 0.05).

Table 3.4. Daily weather conditions at Hays, KS during the application period (June 29 to July 8, 2025).

Date	Max temp (°C)	Min temp (°C)	RH (%)	Precip (mm)	Avg wind (m/s)	Max wind (m/s)	Solar ($MJm^{-2}d^{-1}$)
06-29	36.8	18.2	46.6	0	2.5	8.1	29.2
06-30	30.3	18.0	64.9	1.78	3.4	14.6	24.0
07-01	32.9	22.8	44.9	0	4.1	10.6	22.5
07-02	35.1	24.1	38.2	0	4.8	13.6	37.3
07-03	34.4	18.3	60.3	0	5.1	12.1	26.7
07-04	**30.4**	**19.9**	**73.8**	**0.51**	**5.6**	**11.9**	**16.4**
07-05	36.0	19.8	61.2	0.25	1.9	9.6	27.2
07-06	34.2	19.7	63.4	2.03	2.6	10.4	27.2
07-07	34.5	19.4	58.4	0	2.5	7.9	28.0
07-08	36.8	19.8	55.7	0	2.7	10.0	27.1

Abbreviations: RH, relative humidity; Precip, precipitation; Avg, average; Max, maximum; Solar, solar radiation . Data from Kansas Mesonet, Hays station.

Table 3.5. Palmer amaranth biomass change from pre-application to 21 DAT and analysis of variance p-values at each site-year.

Site-year	n	Pre-application (g)	Post-application (g)	Change (g)	Delta-T	Herbicide	Carrier volume
Manhattan 2024	62	51.4	93.4	+41.9	0.17	0.97	0.25
Hays 2025	47	77.9	44.6	-33.3	0.25	0.01*	0.07
Manhattan 2025	57	57.3	27.5	-29.8	0.70	0.33	0.41

Abbreviations: DAT, days after treatment; n, number of observations; g, grams.

Table 3.6. Estimated marginal means and compact letter displays for soybean yield by herbicide treatment and carrier volume at Hays 2025.

Herbicide	Carrier volume	Yield (kg ha^{-1})
Glufosinate + 2,4-D	187 L ha^{-1}	1,278 a
Glufosinate	187 L ha^{-1}	1,143 ab
Glufosinate	94 L ha^{-1}	1,110 b
Glufosinate + 2,4-D	94 L ha^{-1}	1,083 b

Abbreviation: 2,4-D, 2,4-D choline. Means followed by the same letter are not significantly different ($\alpha = 0.05$). Herbicide × carrier volume interaction $p = 0.027$.

Table 3.7. Environmental conditions at the time of glufosinate application at Manhattan 2024, Hays 2025, and Manhattan 2025. Air temperature, relative humidity, and Delta-T were recorded with a Kestrel 5500AG weather meter.

Site-year	**Application**	**Date**	**Air temperature (°C)**	**Relative humidity (%)**	**Delta-T (°C)**	**Wind speed (Km h^{-1})**
Manhattan 2024	AB	Aug 27	31.1	53.9	12.0	3.7
	CD	Aug 28	29.4	68.5	6.85	0.8
	EF	Aug 31	28.3	74.4	3.65	3.2
	GH	Sep 3	25.0	43.0	12.75	1.2
30-day prior precipitation (mm)	103 mm					
Hays 2025	AB	Jul 1	28.9	42	7.9	8.6
	CD	Jul 2	28.3	54	7.0	14.8
	EF	Jul 4	27.1	74	3.5	13.8
	GH	Jul 4	30.2	62	5.4	22.5
30-day prior precipitation (mm)	52.3 mm					
Manhattan 2025	AB	Jul 7	29.4	70	3.5	3.2
	CD	Jul 10	36.1	58	7.4	4.8
	EF	Jul 15	31.1	70	5.5	3.8
	GH	Jul 17	26.7	79	2.5	6.7
30-day prior precipitation (mm)	133 mm					

Table 3.8. Comparison of the 150 rule (T °F + RH % ≥ 150) and Delta-T classification for each application at Manhattan 2024.

Spray date	Delta-T (°C)	Temp (°F)	RH (%)	T + RH	150 rule met (≥150)	Delta-T optimal (2–8 °C)	Mean control (%)
EF (8/31)	3.65	83	74.4	157.4	Yes	Yes	94.0
CD (8/28)	6.85	85	68.5	153.5	Yes	Yes	90.7
AB (8/27)	12.0	88	53.9	141.9	No	No	29.7
GH (9/3)	12.75	77	43.0	120.0	No	No	89.1

Table 3.9. Comparison of the 150 rule and Delta-T classification for each application at Hays 2025.

Spray date	Delta-T (°C)	Temp (°F)	RH (%)	T + RH	150 rule met (≥150)	Delta-T optimal (2–8 °C)	Mean control (%)
AB (7/1)	7.9	84	42	126	No	Yes	86.3
CD (7/2)	7.0	83	54	137	No	Yes	85.0
EF (7/4)	3.5	80.8	74	154.8	Yes	Yes	42.8
GH (7/4)	5.4	86.3	62	148.3	No	Yes	57.3

Table 3.10. Comparison of the 150 rule and Delta-T classification for each application at Manhattan 2025.

Spray date	Delta-T (°C)	Temp (°F)	RH (%)	T + RH	150 rule met (≥150)	Delta-T optimal (2–8 °C)	Mean control (%)
AB (7/7)	3.5	85	70	155	Yes	Yes	90.6
CD (7/10)	7.4	97	58	155	Yes	Yes	87.2
EF (7/15)	5.5	88	70	158	Yes	Yes	83.4
GH (7/17)	2.5	80	79	159	Yes	Yes	85.0

Chapter 4 - Summary and Conclusions

The research presented in this thesis addressed two practical challenges that Kansas soybean growers face when managing large Palmer amaranth with glufosinate-based postemergence programs in Enlist E3 soybean. The first is that single applications of glufosinate, a contact herbicide, achieve insufficient control of Palmer amaranth that has exceeded recommended spray heights. The second is that glufosinate efficacy is sensitive to atmospheric conditions at the time of application, yet growers have had limited field-tested guidance for deciding conditions that are suitable for spraying.

The sequential application study (Chapter 2) demonstrated that the most reliable path to controlling 20 to 30 cm Palmer amaranth is committing to a second postemergence application. Across four site-years, sequential programs averaged 99 and 98% control in 2024 and 2025, respectively, compared with 95 and 86% for single applications. The magnitude of the sequential advantage varied across years but was significant in both. Within the sequential programs, neither the first-pass herbicide, the second-pass herbicide, nor the interval between applications (3, 10, or 14 days) influenced final Palmer amaranth control. This finding has direct management relevance because it means that a grower who is delayed by weather or competing field operations can still achieve effective control as long as the second pass reaches the field within a 14-day window. At the Hays location in 2025, where weed pressure was highest, the sequential advantage extended beyond visual control ratings: sequential programs preserved 316 kg ha^{-1} of soybean yield and reduced Palmer amaranth biomass by nearly 72% relative to single applications.

The Delta-T study (Chapter 3) evaluated whether a single composite metric of atmospheric evaporative demand could predict glufosinate performance under field conditions.

At Manhattan in 2024, where Delta-T values ranged from favorable to extreme (3.7 to 12.8 C), the relationship was clear: applications within the 2 to 8 C recommended range achieved 92% Palmer amaranth control, while those above 8 C averaged 59%. Each 1 C increase in Delta-T corresponded to a 3.9 percentage point decline in control. However, Hays in 2025 revealed the limits of this metric. Despite all applications falling within the optimal Delta-T range, mean control reached only 68%. Reduced pre-application rainfall and lower solar radiation, not spray-day atmospheric demand, explained the poor performance. At that site, adding 2,4-D choline and increasing carrier volume to 187 L ha^{-1} both significantly improved control, demonstrating that tank-mix composition and application technique can compensate when environmental stress has conditioned the target weed population against a contact herbicide.

Taken together, these two studies converged on a common theme: the reliability of glufosinate-based Palmer amaranth management depended less on optimizing which specific products are applied and more on the operational decisions surrounding the application. Making a second pass, spraying under favorable atmospheric conditions, adjusting carrier volume when conditions are marginal, and adding a systemic herbicide partner when plant stress may limit contact activity are all decisions a grower controls in real time. None of these adjustments require new technology or additional regulatory approval. They require planning, attention to field conditions, and a willingness to return to the field.

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