University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Department of Agronomy and Horticulture: Dissertations, Theses, and Student Research

Agronomy and Horticulture, Department of

7-2024

Evaluating a recision Sprayer for Detecting Weeds and Spraying Herbicides in Real Time (Spot Spray) for Weed Management in Corn and Soybean

Adam Ertic Leise
University of Nebraska-Lincoln

Follow this and additional works at: https://digitalcommons.unl.edu/agronhortdiss

Part of the Agricultural Science Commons, Agronomy and Crop Sciences Commons, Horticulture Commons, Plant Biology Commons, and the Weed Science Commons

Leise, Adam Ertic, "Evaluating a recision Sprayer for Detecting Weeds and Spraying Herbicides in Real Time (Spot Spray) for Weed Management in Corn and Soybean" (2024). *Department of Agronomy and Horticulture: Dissertations, Theses, and Student Research*. 261.
https://digitalcommons.unl.edu/agronhortdiss/261

This Thesis is brought to you for free and open access by the Agronomy and Horticulture, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Department of Agronomy and Horticulture: Dissertations, Theses, and Student Research by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Evaluating precision sprayer for detecting weeds and spray herbicides in real time (target spray) for weed management in corn and soybean

by

Adam Eric Leise

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professor Amit Jhala

Lincoln, NE

July 2024

Evaluating precision sprayer for detecting weeds and spray herbicides in real time (target spray) for weed management in corn and soybean

Adam E. Leise, M.S.

University of Nebraska, 2024

Advisor: Amit Jhala

Herbicide sprayers are becoming larger and more efficient in applications in crop fields. A precise and efficient herbicide application is advantageous in effective weed control. New precision sprayers were introduced in hopes of reducing the amount of herbicide applied. Greeneye Technology and John Deere have developed precision sprayers for the detection of weeds in crop fields, which come equipped with a dual tank system that allows for two different herbicides to be separated from tank to tip. The objectives of this study were to evaluate the broadleaf and grass weed control efficacy of spot spray (SS) technology when applied in spot application versus broadcast application as well as herbicide savings. Greeneye technology's SS machine achieved similar control of palmer amaranth (amaranthus palmeri) (99%) and giant foxtail (setaria faberi) (94-99%) 21 days after POST. When using the John Deere SS machine in 2023, weed control of various broadleaves were similar when comparing SS against broadcast both 21 days after early-POST (A) and late-POST (B). Non-residual herbicide savings were much higher in 2022, achieving 87-94% savings, compared to the highest herbicide saved in 2023 of 5.4%. With early season applications of residual herbicides in 2022, and no residual herbicides applied in 2023, herbicide savings can be directly linked to weed pressure at application timing.

The objectives of the next two studies were to use the dual tank design to separate graminicides (clethodim and quizalofop-p-ethyl) from commonly applied POST herbicides in corn (2,4-d choline) and soybean (dicamba) to reduce antagonism. In soybean, the physical separation of herbicides in dual tank applications provided 71-76% higher control of volunteer corn than tank-mix treatments at 28 days after application. In corn, the separation of herbicides using a dual tank system did provide 93-99% volunteer corn control but was not significantly different from tank-mix treatments. The results from these studies suggest that a dual tank design may mitigate antagonism.

ACKNOWLEDGEMENTS

I would like to express gratitude and thanks to my advisor, Dr. Amit Jhala, who gave me a position during my undergraduate years when I was just a freshman many years ago. This journey, from undergraduate to M.S., has allowed my interest in this field to blossom into what it is today. Through the many years of working for a generous, patient, and kind individual, Dr. Jhala has shown me an astounding example of how to lead others in this field. The knowledge, skills, and experiences I have gained from this journey will allow me to succeed in my next position, and hopefully instill in others a passion for obtaining agricultural knowledge. Also, I would like to thank Dr. Mandeep Singh for his continuous patience, guidance, and advice through all aspects of my M.S. journey. Furthermore, I would like to thank my committee members, Dr. Nicolas Cafaro La Menza and Dr. Stevan Knezevic, for their support and willingness to push me for excellence.

I would also like to thank God and my faith life for keeping me hopeful and grounded during both good and uneasy days, making me everything I am today. My wife, Haley Leise, has been with me each and every day of this journey with full and undivided support of this end goal. I would not be who I am today without her support. I would also like to thank all of my lab members for who I have worked with- Dr. Debalin Sarangi, Dr. Parminder Chahal, Dr. Zahoor Ganie, Will Neels, Trey Stephens, Jasmine Mausbach, Adam Striegel, Shawn Mcdonald, Dr. Jose de Sanctis, Vipin Kumar, Sai Suvidh, and Dr. Ramandeep Kaur- all of which contributed in unique ways to a great work environment of which made this journey that much more enjoyable. Finally, I would like to thank my parents and family, Randy and Mary Leise, for their unending

support in this decision and for being role models in hopes that I can instill virtuous characteristics in others.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction and Objectives

Introduction

Herbicide Application and Techniques

Herbicides have been an effective form of weed control since their introduction, with compounding research leading to a reduction in use rates as well as the discovery of new modes of action (Rüegg et al., 2007). With this, the first herbicide-resistant (HR) crop introduced was in 1995, with glyphosate-resistant soybean introduced just a year later in 1996, and glyphosate-resistant corn in 1998 (Duke, 2005; Nandula, 2019). Following this introduction of HR crops came a swift adoption, with farmers quickly realizing the benefits at play including higher yield and profitability (Green, 2012). This combination of herbicides to control weeds paired with the respective HR crop is a great option, especially in corn-soybean rotations. Boom sprayers were adopted for herbicides in the mid-20th century (Bals, 2018). Ever since this adoption, research about increased efficiency, nozzle selection, and productivity has been widely discussed. Applicators need to understand the proper hection breakrbicide application fundamentals (Dhananjayan et al., 2020), with failures in either equipment or improper techniques allowing for off-target movement (Oseland et al., 2024; Jones et al., 2019), inadequate weed coverage (Creech et al., 2018) or potential harm to groundwater (New-Aaron et al., 2021). While boom sprayers become bigger, faster, and more efficient, adequate spray coverage for weed control while mitigating these potential risks should be priority.

Advancement of Precision Sprayers

The evolution of patch or site-specific herbicide applications has been widely discussed (Gutjahr et al., 2012; Wiles, 2009; Tian et al., 1999). These sprayers aim to predict the scope of weed pressure in certain areas of the field and apply the appropriate amount of herbicide when needed. Potential benefits of this application method are highlighted by the reduction of herbicide use (Nordmeyer, 2006; Rider et al., 2006), which leads to many incentives for those involved. Recent advancements have progressed this technology even further, with precision sprayers now introduced in the market. A precision sprayer uses machine vision and algorithms to identify or detect weeds in real time (Vijayakumar et al., 2023), only applying herbicide when weeds are present. This advancement implies benefits which include further reduction of herbicide, less off-target movement, less potential for crop injury, and increased efficiency (Gullickson, 2022) relaying benefits for both the farmer and environmental purposes. The precise detection of weeds and relay to trigger proper nozzle spray is ideal in these machines. While herbicide savings are the highlight of these machines, proper weed control is a priority. Two of the newest spot spray machines that have become available in the market include the John Deere See and Spray™ package (Deere and Company, Moline, IL) and Greeneye Technology™ (Greeneye Technology, Tel Aviv, Israel). Both machines claim to be effective in corn and soybean row cropping systems, a popular choice among farmers in the Midwest. John Deere's See and Spray Ultimate™ is an all-in-one machine that comes equipped with this technology (Gullickson, 2022), while Greeneye Technology is a boom only system that can be retrofitted onto an existing sprayer (Miller, 2022). With this, the proper detection of weeds and spot spray herbicide applications with these two machines should be tested in diverse cropping systems and multiple weed scenarios.

Dual Tank Technology to Alleviate Antagonism

In instances with both grass and broadleaf weed pressure, multiple modes of action are needed for effective control of each species. Herbicide antagonism, as defined by Colby (1967), pertains to a herbicide having a lower-than-expected efficacy when tank mixed with another herbicide, as compared against just one herbicide. Most commonly, this antagonism reduces the efficacy to control monocot plants (Zhang et al., 1995). As each individual herbicide possesses a unique chemical structure, this makes the combination of selected herbicides distinctive in nature that need to be analyzed whether to be antagonistic. While the introduction of HR crops has opened the doors for multiple modes of action to be applied simultaneously, HR crop volunteers the following year require special attention. HR volunteer corn, specifically glufosinate/glyphosate-resistant volunteer corn, is typically controlled with graminicides (grass herbicides) (Striegel et al., 2020) which include herbicides in the FOP, DIM, and DEN families. However, antagonism between selected graminicides, specifically quizalofop-p-ethyl and clethodim, and common broadleaf herbicides, such as 2,4-d choline and dicamba, has been widely noted (Singh et al., 2023; Underwood et al., 2016; Duenk et al., 2023). Herbicide interactions can occur in the tank, on the leaf of the plant, or inside the plant (Barbieri et al., 2022). The precision sprayers come equipped with two separate tanks and boom systems, which keep herbicides physically separate from ‘tank to tip’. This may be beneficial if the herbicide antagonism is a tank compatibility issue. Knowing the multitude of unique herbicide interactions, each herbicide combination needs to be evaluated to understand where antagonism occurs.

OBJECTIVES

1. Evaluate the broadleaf and grass weed control efficacy of spot spray (SS) technology when applied in spot application versus broadcast application as well as herbicide savings.
2. Evaluate efficacy of quizalofop-p-ethyl applied in a separate tank (dual tank) using the precision dual tank sprayer or mixed with 2,4-D choline in the same tank (tank-mix) and apply for control of glufosinate/glyphosate-resistant corn volunteers in corn resistant to arloxyphenonxypropionates.
3. Evaluate efficacy of clethodim applied in a separate tank (dual tank) using the precision dual tank sprayer or mixed with dicamba in the same tank (tank-ix) and apply for control of glufosinate/glyphosate-resistant corn volunteers in dicamba/glufosinate/glyphosate-resistant soybeans.

Literature Cited

Bals, E. (2018). Pesticide application equipment: 60 years of history. *International Pest Control*, *60*(2)-96.https://www.proquest.com/openview/71d9adf21722d9d55be3e98c4f1f7897/1?pq-origsite=gscholar&cbl=2029999

Barbieri, G. F., Young, B. G., Dayan, F. E., Streibig, J. C., Takano, H. K., Merotto Jr., A., & Avila, L. A. 2022). Herbicide mixtures: interactions and modeling. *Adv Weed Sci*, *40*(spe1), 10.51694/AdvWeedSci/2022;40

Creech, C. F., Henry, R. S., Hewitt, A. J., & Kruger, G. R. (2018). Herbicide Spray Penetration into Corn and Soybean Canopies Using Air-Induction Nozzles and a Drift Control Adjuvant. *Weed Technology*, *32*(1), 72–79. https://doi.org/10.1017/wet.2017.84

Colby, S. R. (1967). Calculating Synergistic and Antagonistic Responses of Herbicide Combinations. *Weeds (Urbana)*, *15*(1), 20–22. https://doi.org/10.2307/4041058

Deere and Company, 2024.https://www.deere.com/en/sprayers/see-spray-ultimate/

Dhananjayan, V., Jayakumar, S., Ravichandran, B. (2020). Conventional Methods of Pesticide Application in Agricultural Field and Fate of the Pesticides in the Environment and Human Health. In: K. R., R., Thomas, S., Volova, T., K., J. (eds) Controlled Release of Pesticides for Sustainable Agriculture. Springer, Cham. https://doi.org/10.1007/978-3-030-23396-9_1

Duenk, E., Soltani, N., Miller, R., Hooker, D., Robinson, D., Sikkema, P. (2023). Synergistic and Antagonistic Herbicide Interactions for Control of Volunteer Corn in Glyphosate/Glufosinate/2,4-D-Resistant Soybean. (n.d.). *Journal of Agricultural Science (Toronto)*. https://doi.org/10.5539/jas.v15n4p27

Duke, S.O. (2005), Taking stock of herbicide-resistant crops ten years after introduction. Pest. Manag. Sci., 61: 211-218. https://doi.org/10.1002/ps.1024

Green, J.M. (2012), The benefits of herbicide-resistant crops. Pest. Manag. Sci., 68: 1323-1331. https://doi.org/10.1002/ps.3374

Gullickson, G. (2022). John Deere's See and Spray Ultimate cuts chemical use by targeting weeds with precision spraying. Successful Farming, https://www.agriculture.com/technology/john-deere-s-see-spray-ultimate-cuts-chemical-use-by-targeting-weeds-with-precision

Gutjahr, C., Sökefeld, M., & Gerhards, R. (2012). Evaluation of two patch spraying systems in winter wheat and maize. *Weed research*, *52*(6), 510-519. https://doi.org/10.1111/j.1365-3180.2012.00943.x

Jones, G. T., Norsworthy, J. K., Barber, T., Gbur, E., & Kruger, G. R. (2019). Off-target Movement of DGA and BAPMA Dicamba to Sensitive Soybean. *Weed Technology*, *33*(1), 51–65. https://doi.org/10.1017/wet.2018.121

Miller, D. (2022). Smart Sprayer Technology. Progressive Farmer. https://www.dtnpf.com/agriculture/web/ag/news/article/2022/02/10/smarter-sprayers

Nandula, V.K. (2019). Herbicide Resistance Traits in Maize and Soybean: Current Status and Future Outlook. *Plants* 2019, *8*, 337. https://doi.org/10.3390/plants8090337

New-Aaron, M., Abimbola, O., Mohammadi, R., Famojuro, O., Naveed, Z., Abadi, A., Bell, J. E., Bartelt-Hunt, S., & Rogan, E. G. (2021). Low-level groundwater atrazine in high atrazine usage nebraska counties: Likely effects of excessive groundwater abstraction. *International Journal of Environmental Research and Public Health*, *18*(24), 13241-. https://doi.org/10.3390/ijerph182413241

Nordmeyer, H. (2006). Patchy weed distribution and site-specific weed control in winter cereals. *Precision Agriculture*, *7*(3), 219–231. https://doi.org/10.1007/s11119-006-9015-8

Oseland, E., Bish, M., Lerch, R., & Bradley, K. (2024). Atmospheric deposition of dicamba herbicide can cause injury to sensitive soybean. *Weed Science*, 1–10. https://doi.org/10.1017/wsc.2024.9

Rider, T. W., Vogel, J. W., Dille, J. A., Dhuyvetter, K. C., & Kastens, T. L. (2006). An economic evaluation of site-specific herbicide application. *Precision Agriculture*, *7*(6), 379–392. https://doi.org/10.1007/s11119-006-9012-y

Rüegg, W. T., Quadranti, M., & Zoschke, A. (2007). Herbicide research and development: challenges and opportunities. *Weed research*, *47*(4), 271-275. https://doi.org/10.1111/j.1365-3180.2007.00572.x

Singh, M., Kumar, V., Knezevic, S. Z., Irmak, S., Lindquist, J. L., Pitla, S., & Jhala, A. J. (2023). Interaction of quizalofop-p-ethyl with 2,4-D choline and/or glufosinate for control of volunteer corn in corn resistant to aryloxyphenoxypropionates. *Weed Technology*, *37*(5), 471–481. doi:10.1017/wet.2023.79

Striegel, A., Lawrence, N. C., Knezevic, S. Z., Krumm, J. T., Hein, G., & Jhala, A. J. (2020). Control of glyphosate/glufosinate-resistant volunteer corn in corn resistant to aryloxyphenoxypropionates. *Weed Technology*, *34*(3), 309–317. https://doi.org/10.1017/wet.2020.41

Tian, L., Reid, J. F., & Hummel, J. W. (1999). Development of a precision sprayer for site-specific weed management. *Transactions of the ASAE*, *42*(4), 893-900.doi: 10.13031/2013.13269

Vijayakumar, V., Ampatzidis, Y., Schueller, J. K., & Burks, T. (2023). Smart spraying technologies for precision weed management: A review. *Smart Agricultural Technology*, 100337. https://doi.org/10.1016/j.atech.2023.100337

Wiles, L. J. (2009). Beyond patch spraying: site-specific weed management with several herbicides. *Precision Agriculture*, *10*, 277-290.https://doi.org/10.1007/s11119-008-9097-6

Underwood, M. G., Soltani, N., Hooker, D. C., Robinson, D. E., Vink, J. P., Swanton, C. J., & Sikkema, P. H. (2016). The Addition of Dicamba to POST Applications of Quizalofop-p-ethyl or Clethodim Antagonizes Volunteer Glyphosate-Resistant Corn Control in Dicamba-Resistant Soybean. *Weed Technology*, *30*(3), 639–647. https://doi.org/10.1614/WT-D-16-00016.1

Zhang, J., Hamill, A. S., & Weaver, S. E. (1995). Antagonism and synergism between herbicides: trends from previous studies. *Weed Technology*, *9*(1), 86–90. https://doi.org/10.1017/s0890037x00023009

Evaluating precision sprayers for detecting weeds and applying herbicides in real time for target weed control in corn and soybean fields

Adam Leise

Abstract

A precise and efficient method for herbicide application in commercial crop fields is desirable for financial and environmental purposes. Precision sprayers have been developed with cameras and sensors built into the sprayer that detect weeds in real time followed by targeted spraying of herbicide. The objective of this study was to evaluate spot spray (SS) technology compared to traditional broadcast application of pre-plant, early post-emergence (EPOST), and late-POST (LPOST) herbicides for broadleaf and grass weed control in corn and soybean fields. Greeneye Technology's precision sprayer was evaluated in corn field near Clay Center, NE in 2022 and John Deere's precision sprayer was evaluated in soybean field near Mead, NE in 2023. In 2022, Palmer amaranth (*Amaranthus palmeri* S. Watson) and giant foxtail (*Setaria faberi* Herrm.) control was similar between SS (94%-99%) and broadcast (99%) 21 d after LPOST herbicide application. In 2023, common lambsquarters (*Chenopodium album* L.), kochia [*Bassia scoparia* (L.) A.J. Scott], and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] control and soybean yield was similar between SS and broadcast 21 d after LPOST. Herbicide savings varied between site-years depending on weed infestation at the time of herbicide application. It could be attributed to relatively lower weed pressure due to residual herbicide use in 2022 but no residual herbicide was applied in 2023, resulting in high weed infestation at the time of LPOST herbicide application. The results suggest that precision sprayers were very accurate in detecting weeds and applying herbicides and would be rewarding in fields with low weed infestation.

Introduction

Herbicides are commonly used to control weeds in large-scale farming in the USA and several other countries due to the ease of implementation and being an effective and economical method in crop fields (Pacanoski, 2007; Lyon et al., 1996). Herbicides share a significant portion of input in row cropping systems. For example, in 2022, estimated costs for herbicide programs in corn, cotton, and soybean were \$123 ha^{-1}, \$206 ha^{-1}, and \$200 ha^{-1}, respectively (Greogry & Leach, 2022). The use of herbicides can effectively enhance crop yield by controlling weeds; however, ineffective or overuse of herbicides comes at a risk to human health and environment (Damalas & Eleftherohorinos, 2011; Yarpuz-Bozdoğan, 2018). A risk assessment of commonly used herbicides such as atrazine, glyphosate, and dicamba suggests an increasing cause of concern for human health risks due to herbicide exposure (Gammon et al., 2005; Lerro et al., 2020). Considering an increase in herbicide prices and associated potential risks to humans and the environment, the use of the least amount of herbicide would be beneficial.

The use of large broadcast sprayers has been an effective method for applying herbicides in cash crop fields in recent decades in the USA. Advancements in broadcast sprayers such as application technology, sprayer size and speed, and tank volume have made it possible to cover more acres than ever before; however, these advancements come with potential side effects such as more horizontal trajectory and potential for drift (Sapkota et al., 2009). Spray drift is one of the primary mechanisms of pesticide off-target movement (Matthews et al., 2014). Despite best efforts to mitigate spray drift, off-target movement through particle drift continues to be a major issue in the USA (Werle et al., 2022). With an increasing squeeze on herbicide regulations, it is important to have a precise and efficient application of herbicides as their use is prevalent in row cropping systems.

Precision sprayers have been developed to help reduce herbicide use, input costs, and subsequently environmental risks associated with the overuse of herbicides. For example, variable-rate smart sprayers have been shown to reduce herbicide use compared to a constant rate, conventional broadcast (Hussain et al., 2020). Greeneye Technology (Greeneye Technology, Tel Aviv, Israel) and John Deere (Deere & Company, Moline, IL) have developed precision sprayers that have attached cameras and processing units that can detect weeds in real-time and spray herbicide. Greeneye Technology refers to their machine as the “Greeneye Sprayer” which is a boom that can be mounted onto a sprayer that is compatible. This system is programmed to identify weed species, activating the nozzles when necessary. This design differs from John Deere, which has developed a precision sprayer all-in-one machine (ASABE, 2022). This system detects when there are weeds between the cash crop rows, activating the nozzles when weed is present. This technology, which will be referred to as “spot spray” (SS) or target spray, is equipped with two large volume tanks that carry a soil residual and non-residual herbicide in separate tanks. This setup allows applications of only spray non-residual foliar-active herbicides when cameras identify a weed species or detect weed presence (Vogt, 2022). The sensitivity for weed identification or detection can be changed depending on what coverage the applicator is looking for. It is important to test the efficiency and efficacy of precision sprayers for weed control compared to a traditional broadcast sprayer in corn and soybean fields. Depending on the weed infestation, precision sprayers can reduce the amount of non-residual herbicides sprayed post-emergence in cash crop fields (Spaeth et al., 2024). If effective, this is considered a win-win for the environment and reduces herbicidal input cost for farmers. While a precise application is in reach, it is critical to have a timely and adequate rate of herbicides when using target precision sprayers.

John Deere and Greeneye precision sprayers are currently designed for 76 cm row spacing crops such as corn, soybean, and cotton. The study's objectives were to evaluate the broadleaf and grass weed control efficacy of precision sprayers when applied in spot (target) application versus broadcast application and herbicide savings. We hypothesized that SS would perform at or near the level of a traditional broadcast setup in terms of weed control after applications in fields with various weed infestations. Furthermore, we hypothesized that SS would reduce herbicide costs in fields with low weed infestation, given a program that includes a residual herbicide. The goal of the study was to detect current SS capabilities, while also recommending future advancements.

Materials and Methods

Machine Design

Greeneye Technology has developed a boom-only SS system that retrofits onto sprayers (Figure 1). This system allows itself to be adaptable in different operations. The boom consists of 24 cameras controlling 144 nozzles on a 37 m wide boom. The system has a dual tank/line system installed, which allows herbicide from Tank 1 and Tank 2 to be separated from ‘tank to tip’. This allows select applications to occur at the operator's action. The central processing units can detect weeds in real-time at a maximum speed up to 24 km h^{-1}.

The John Deere’s See and Spray package is factory-installed on four different model tractor sprayers (410R, 412R, 612R, and 616R) (Fischer, personal communication, 2023). This system is designed currently for detecting weed infestation, instead of identifying individual weed species. The John Deere 612R model was used for this experiment, with a total boom length of 37 m including 96 nozzles and 36 cameras (Figure 2 and Figure 3). Since the plot width was 18 m, the boom was folded in half during herbicide applications. Nozzle spacing is designed at 38 cm, which includes a nozzle directly over the row crop. Sensitivity, the height at which weeds are detected and sprayed, can be modified to turn on multiple nozzles per row or detect smaller weeds (6 mm). Multiple nozzle activation is handy in windy conditions which is a common occurrence in spring months in Nebraska. Sensitivity can be adjusted to modify the length of application; and the amount of time the sprayer is spraying the detected weeds. These adjustments will affect weed control and concurrently the amount of herbicide applied or saved. The data from 36 cameras run back to vision processing units to confirm the nozzles to act. If the confidence of camera falls due to any reason, the nozzle units will enter ‘fallback mode’ to which the sprayer applies herbicide in a broadcast method until the camera regains confidence. This is to ensure there are no weed escapes. The precision sprayer has a dual tank system; Tank 1 and Tank 2. Tank 1 is a 2,839 liter (L) capacity tank, which is larger than Tank 2’s 1,703 L capacity. Tank 1 is preferred for a blanket broadcast herbicide application while Tank 2 may be used for SS or spot (target) applications. Tanks 1 and 2 have separate nozzles; at no point does the machine spray two different herbicides through the same nozzle. This may be an important factor in potentially reducing herbicide antagonism when controlling weed species by applying two herbicides at the same time. The SS system is labeled for application up to 19 km h^{-1} in 2023, with an expected 24 km h^{-1} speed coming in the next generation precision sprayers. Boom height is preferred to be between 61 and 76 cm above the weeds. This is the range the cameras are deemed most accurate. If the boom enters outside this boundary due to uneven terrain, it will enter fallback mode, which applies herbicide in a full broadcast method.

Experimental Site

The field trials were conducted at the University of Nebraska-Lincoln's South-Central Agricultural Laboratory (SCAL) near Clay Center, NE (40.52° N, 98.05°W) in 2022 to test Greeneye Technology's precision sprayer, and at the Eastern Nebraska Research Extension and Education Center (ENREEC) near Mead, NE (41.8°N, 96.29°W) in 2023 to test John Deere's precision sprayer. Trials were set up in a completely randomized design due to the large plot size and boom length of the precision sprayers. In 2022, three separate studies were conducted at Sout Central Ag Lab. Three treatments were replicated three times, with four pseudo-replications in each replication. Treatments comprised of different application techniques consisting of Broadcast only (using Tank 1 only), Broadcast (Tank 1) + SS (Tank 2), Broadcast (Tank 1) + Broadcast (Tank 2). For each application technique, herbicides were applied as an early-POST (EPOST) and a late-POST (LPOST) (Table 1). In 2023, four herbicides, each applied as broadcast and SS comprised eight treatments, which were replicated two times, with four pseudo-replications in each replication. Herbicides were applied EPOST and a LPOST (Table 2). The broadcast application of each herbicide was placed directly beside the SS consisting of the same herbicide. This was accomplished hoping to have similar weed infestation before herbicide applications. For the feasibility of applying herbicides with larger commercial sprayers, the plot size was 18 × 45 m at Clay Center, NE and 18 × 76 m at Mead, NE.

In 2022, glufosinate/glyphosate-resistant corn (DKC60-87RIB RR/LL; Dekalb Genetics Crop, Dekalb, IL) was planted on April 28 in fields with irrigated, ridge-till conditions in 76 cm row spacing. Flumioxazin (Valor SX; Valent USA, San Ramon, CA) at 71 g active ingredient (ai) ha^{-1} was applied in the fall of 2021 after soybean harvest which provided control of winter annual weeds. The EPOST application occurred on May 17. Acetochlor/atrazine (Harness Xtra; Bayer Crop Science, Research Triangle, NC) at 4,033 g ai ha^{-1} and mesotrione (Callisto;

Syngenta Crop Protection, Greensboro, NC) at 165 g ai ha^{-1} including ammonium sulfate (AMS) 2.5% v/v and crop oil concentrate (COC) 1% v/v were placed in Tank 1 to provide residual weed control, being applied to 100% of the treatment plot area (Table 1). Tank 2, which was the SS-designated tank (target spray), consisted of dicamba (DiFlexx; Bayer Crop Science, Research Triangle, NC) at 350 g acid equivalent (ae) ha^{-1} and glyphosate (Roundup PowerMax; Bayer Crop Science, Research Triangle, NC) at 945 g ae ha^{-1} along with AMS 2.5% v/v and non-ionic surfactant (NIS) 0.25% v/v. The LPOST herbicide application occurred on June 13. Tank 1 was activated 100% of the time and included acetochlor/atrazine at 1,344 g ai ha^{-1} atrazine (AAtrex 4L; Syngenta Crop Protection, Wilmington, DE) at 448 g ai ha^{-1}, and mesotrione at 105 g ai ha^{-1} along with AMS 2.5% v/v and COC 1% v/v. Tank 2 was the designated SS (target spray), which included dicamba/diflufenzopyr (Status; BASF, Research Triangle Park, NC) at 196 g ai ha^{-1} and glyphosate at 945 g ae ha^{-1} + AMS 2.5% v/v + NIS 0.25% v/v. Tank 2 was not active for both A and B applications in 'Broadcast only' treatment. The average sprayer speed was 13 km h^{-1} and spray volume for both applications was 187 L ha^{-1}, respectively. AIXR 11015 flat fan nozzles (TeeJet Technologies; Spraying Systems Co.) were used for Tank 1 applications, while custom-made DG4003 large droplet nozzles (TeeJet Technologies) were used for Tank 2 applications which are recommended for dicamba application to reduce drift (Sousa et al., 2017).

Enlist E3™ soybean (Stine 32EE21; Stine Seed Company, Adel, IA) was planted in 76-cm spaced rows on May 9, 2023, with the field being in no-till, rainfed conditions. The EPOST application was applied on the day of planting on May 9, 2023. To fully determine the effectiveness of SS and push the boundaries of the technology with high weed infestation, no herbicide with residual activity was applied in this application. LPOST was applied on June 20, 2023. The average sprayer speed and spray volume for both applications were 15 km h^{-1} and 187

L ha^{-1}, respectively. Specific herbicides applied in both applications are listed in Table 2. Besides 2,4-D choline, AMS 3% v/v was mixed with each herbicide treatment. Glyphosate and lactofen (Cobra; Valent USA LLC, San Ramon, CA) included NIS 0.25% v/v, and saflufenacil contained methylated seed oil (MSO) 1% v/v. Due to high weed infestation at the time of LPOST application, glufosinate rate was increased to 881 g ai ha^{-1} to control weeds assuming they will be taller than the height at EPOST application timing. Acetochlor (Warrant; Bayer Crop Science) at 1,513 g ai ha^{-1} was broadcast applied in the entire field in a separate tank during application B to provide residual weed control coupled with the non-residual herbicides. The nozzles used for all broadcast applications were PSLDMQ2006 low drift nozzles (John Deere), with AIXR 11004R4 nozzles (TeeJet Technologies) used for SS applications. These nozzles were rear facing at 40° angle.

Weed size and environmental conditions at herbicide application

In 2022, weed sizes ranged from cotyledon to 3 cm tall at the time of EPOST application and wind speed was 3-10 km h^{-1}. During LPOST, weed sizes ranged from 3-15 cm tall and an average wind speed was 15 km h^{-1}. Weed pressure was minimal at the time of LPOST application due to a strong residual herbicide program in LPOST application that was broadcasted in 100% of the experimental site.

In 2023, weed size ranged from 1-7 cm tall at the time of the EPOST application. Wind speed was moderate at 8-15 km h^{-1}. The sensitivity of the machine which determines what weed size is picked up in the SS program was set to ‘low’. At LPOST application, weed size displayed a high variance between the cotyledon stage to 91 cm. The highest weed height and pressure was of kochia [*Bassia scoparia* (L.) A.J. Scott]. Since no residual herbicide was applied, the escapes from application A provided high weed pressure. The wind speed was 11 to 13 km h^{-1}.

Data Collection

In 2022 field studies, weeds present included Palmer amaranth (Amaranthus *palmeri* S.Watson) and giant foxtail (*Setaria faberi* Herrm.). In 2023, weeds present included common lambsquarters (*Chenopodium album* L.), kochia and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer]. Weed control estimates were taken at 7, 14, and 21 days after LPOST application in 2022, and 7, 14, and 21 days after EPOST and LPOST in 2023, on a scale of 0% to 100% where 0% indicates no control of weeds, and 100% indicates complete control. Weed density was determined by counting plants in two one m^2 quadrats side by side, in a random and representative area of the plots 7, 14, and 21 DAB in 2022, and 14 days after each treatment in 2023. Herbicide applied per area was determined after each application timing from each machine's data center in both years, on a scale of 0%-100%, with 0% indicating the SS was active during the entire application, and 100% indicating the SS did not spray any herbicide. Then, the percent area coverage with SS was converted to percent herbicide savings by deducting it from 100%. In 2022, corn was harvested using a John Deere 9570, and in 2023, soybean was harvested using a John Deere S650 combine. Corn and soybean yields were adjusted to a standard moisture content of 15.5% and 13%, respectively. Using ArcGIS PRO version 3.2 (Ersi GIS Mapping Systems, Redlands, CA), Crop yield maps were categorized for each treatment.

Data Analysis

Data were analyzed using SAS Studio, version 9.4 (SAS Institute, Cary, NC). Data were separated by year and analyzed using the PROC GLIMMIX procedure. There was no difference in weed control between three projects conducted in 2022; therefore, data were combined. The application technique was treated as a fixed effect, while block was treated as a random effect. For 2023, herbicide and application technique combination were treated as a fixed effect, while block was treated as random effects. Type III tests were conducted to assess fixed effects and treatment means were separated using LSMEANS with Tukey's test at α=0.05. For 2023, orthogonal contrasts between broadcast and SS were conducted using CONTRAST statement followed by PROC MEANS procedure to find overall means, with significance determined at α=0.05.

Results & Discussion

Weed Control

Broadcast + SS provided similar control of Palmer amaranth (99%) and giant foxtail (93%) compared to broadcast + broadcast (98%-99%) 7 days after treatment (DAT) of late-post-emergence (LPOST) herbicide application in corn in 2022 (Table 3). Furthermore, control of Palmer amaranth (P= 0.18) and giant foxtail (P=0.23) did not differ from broadcast only, indicating no significant advantage of non-residual herbicides (Tank 2) because weed infestation was minimal at the time of LPOST herbicide application. At 14 DAT of LPOST herbicide, control of Palmer amaranth (99%) and giant foxtail (90%) with broadcast + SS was similar to broadcast + broadcast (99%). At 21 DAT of LPOST, control of giant foxtail and Palmer amaranth with broadcast + spot (94-99%) herbicide application was 17% and 6% higher than broadcast only (77-93%), respectively (Table 3). Spaeth et al. (2024) found that a conventional broadcast application resulted in the same weed control 14 days after application compared to a SS application in corn (98-100%), while SS saved 20% of herbicide in corn. Furthermore, weed coverage and control in sugar beet (*Beta Vulgaris*) between broadcast and SS were similar (95-100%) 14 days after application, saving up to 55% of herbicide. Similarly, in this study, the soil-active herbicide applied EPOST provided excellent weed control that reduced the amount of LPOST herbicide applied. Likewise, corn and soybean studies conducted in Nebraska reported a savings of 64% of non-residual herbicide in soybean, and 43% in corn, while providing similar weed control (Barnhart, 2024). Palmer amaranth control in broadcast + SS application was 5%-9% higher compared to giant foxtail control in the same treatments from 7-21 DAT of LPOST. Buzanini et al. (2023) found that grass weeds may be harder to identify for SS systems, noting that shadows, weed height, and timing of application play an impact on accuracy of weed identification. This notion that grasses may be harder to identify than broadleaf weeds should be tested in future.

In 2023, control of common lambsquarters, waterhemp, or kochia did not differ between broadcast and spot spray applications up to 21 DAT of LPOST (Table 4). Among individual herbicide treatments, 2,4-D choline at 1,284 g ae ha^{-1} did not provide good control of kochia with broadcast (41%) or SS (16%) having 21%-83% lower control than other herbicides (62%-99%) 7 DAT. The 2,4-D choline was not effective, providing a maximum of 38% kochia control, which was similar to glufosinate at 655 g ai ha^{-1} (47%-50%). Similarly, poor control of kochia (25-39% at 30-39 days after treatment) when using 2,4-D has been reported in other studies (Wolf et al., 2000; Tonks & Westra, 1997). Kochia infestation and plant height became an issue in LPOST applications. Reduction in herbicide efficacy for weed control when weeds are taller than mentioned in the label is weel documented (Kouame et al., 2023; Meyer & Norsworthy, 2019). With kochia height (up to 91 cm) in LPOST applications, an increase in glufosinate application rate from 655 g ai ha^{-1} to 881 g ai ha^{-1} was needed. Kumar & Jha (2015) found that glufosinate at 593 g ai ha^{-1} can provide 87% kochia control 7 days after treatment. Saflufenacil provided 94 to 95% control of kochia 21 DAT of EPOST, resulting in minimal infestation that was followed by (fb) 2,4-D choline. At 7 DAT of LPOST, 2,4-D choline had a 3% lower kochia control with SS (95%) than broadcast (98%; Table 5). Similarly, lactofen provided 9% lower kochia control with SS (62%) than broadcast (71%) 14 DAT of LPOST. Weed control of all weed species did not differ among broadcast and SS for all herbicides by 21 DAT of LPOST. These findings correlate with Spaeth et al. (2024) who observed similar weed control between broadcast and SS in corn (98-100%) and sugar beet (95-99%). Buzanini et al. (2024) observed similar findings in plasticulture pepper (*Capsicum annuum ‘Jalapeno’*) production, noting an 84% and 54% non-residual herbicide savings when following a previously applied residual herbicide in the fall and spring, respectively.

Precision sprayer such as custom builds and alternative algorithms, have been tested in turfgrass system and reported to have high precision in the identification of broadleaves such as carpetweed (*Mollugo verticillata* L.), three lobe morningglory (*Ipomea triloba* L.) and common ragweed (*Ambrosia artemisiifolia* L.) (Jin et al., 2023; Yu et al., 2019). These findings suggest that SS systems can have a high accuracy in identifying broad leaves among grass crops. In this study, differences were observed among herbicides with respect to their efficacy for controlling individual weed species; however, no pattern of differences was observed in weed control between broadcast and SS after EPOST and LPOST herbicide applications in our studies, validating the machine could identify weeds in corn in 2022, and detect and target weeds in soybean in 2023.

Weed density

Palmer amaranth and giant foxtail densities were low (0-0.2 plants m^{-2}) following LPOST applications with no differences among application techniques 7 DAT of LPOST in 2022 field study in corn (Table 6). Giant foxtail density was similar at 14 and 21 DAT of LPOST in broadcast + SS (0.3-0.7 plants m^{-2}) compared to broadcast + broadcast (0 plants m^{-2}). Giant foxtail density at 21 DAT of LPOST was higher in broadcast only (2.3 plants m^{-2}) compared to broadcast + broadcast (0 plants m^{-2}). With a PRE and POST herbicide program with residual activity, Palmer amaranth was effectively controlled throughout the growing season, resulting in 0 plant m^{-2} 21 DAT of LPOST in broadcast + SS and broadcast + broadcast herbicide application. In 2023, common lambsquarters density was higher in broadcast (1.4 plants m^{-2}) than SS (1.0 plants m^{-2}) 14 DAT of EPOST (P = 0.09; Table 7). Otherwise, no differences were observed between broadcast and SS for all weed species 14 DAT of EPOST and 14 DAT of LPOST.

Herbicide Savings

In 2022, SS was activated 6% and 13% of the time of EPOST and LPOST applications, saving 94% and 87% of non-residual herbicides, respectively (Table 8). Herbicide savings were high as weed infestation was minimal due to the application of herbicides with diverse modes of action (Table 1). Weed density, growth stage, and species present may have a direct correlation on SS nozzle activation and herbicide savings (Spaeth et al. 2024; Zanin et al. 2022). Gonzalez de Soto et al. (2016) observed that when weed patches cover 22.6% of ground surface in wheat (*Triticum aestivum* L.), a custom roboticized sprayer applied herbicide to 23.1% of the area. This margin for error may be higher or lower with other SS systems, cropping systems, or weed characteristics.

In 2023, non-residual herbicide savings were low (1.1%-5.4%) for EPOST application and none for LPOST application (Table 9). For the EPOST application, the lowest and highest amount of herbicide saved using SS was 1.1% and 5.4% with 2,4-D choline and glyphosate sprayed in 98.9% and 94.6% of the total plot area, respectively. The history in relation to weed control of the experimental field in 2023 provided a high weed infestation at the timing of pre-plant herbicide application. Furthermore, since no residual herbicide was applied at planting, weed infestation during the LPOST herbicide application in 2023 was significantly higher than that of 2022 field studies (Figure 4a and Figure 4b). It has been suggested with other SS technologies that crop stage and how close the crop is to canopy may affect the ability to 'see' between the rows (Barnhart et al. 2024). Jin et al. (2023) developed a linear regression model that states as weed infestation increases (as %), herbicide applied as volume increases. Thus, proper herbicide coverage should be the priority before herbicide savings. Villette et al. (2022) found that SS systems with multiple nozzle activation with double overlap should provide the best herbicide coverage in SS systems compared to an increase in flowrate per nozzle. Furthermore, the activation of adjacent nozzles regarding a specific target prevents the under application of herbicide to weeds. The activation of multiple nozzles regarding spray overlap may directly impact herbicide savings, alluding to further testing needed in this area.

Crop Yield

In 2022, corn yield in broadcast + broadcast was higher (17,219 kg ha^{-1}) than broadcast only (16,366 kg ha^{-1}; Figure 5). Broadcast + SS yield (16,867 kg ha^{-1}) was similar to broadcast +

broadcast yield. In 2023, soybean yield was lowest in 2,4-d choline fb glufosinate in broadcast and SS treatments (4,456-4,893 kg ha^{-1}; Figure 6). Soybean yield in 2,4-D choline fb glufosinate was reduced because of poor control of kochia early in the growing season. Kochia's impact on soybean yield in Nebraska was noted by Wicks et al. (1997), observing that soybean yield will likely decrease for each soybean growth stage kochia is not controlled. In all herbicide combinations, there were no differences in yield between broadcast and SS treatments, indicating SS application of herbicide was as effective as broadcast for wee control and reducing crop-weed competition.

Crop metabolism of herbicide and its impact on yield has been studied (Hamouz et al., 2015) and the use of a precision sprayer to reduce the amount of herbicide applied could lead to a higher yield (Parte et al., 2019). This direct notion that the use of a SS system leading to a higher yield was not found in this study but should be tested in the future.

Practical Implications

Precision sprayers were evaluated in this study for target weed control compared with broadcast application in corn and soybean production fields in Nebraska. Target spray of herbicide provided similar control of Palmer amaranth and giant foxtail as broadcast application in field studies conducted in corn in 2022 (Table 3), saving 87% of herbicides (Table 8). The application of layered residual herbicide provided excellent weed control and a field with minimal weed infestation, which directly influenced herbicide savings. The precision sprayer provided 94 to 99% control of Palmer amaranth and giant foxtail in corn under target application, saving 94% and 87% of herbicide in EPOST and LPOST applications, respectively. In 2023, control of common lambsquarters and waterhemp were similar between broadcast and SS application 7-14 DAT in either application, and kochia control was similar 7-21 DAT of EPOST, and 14-21 DAT of LPOST. Therefore, the precision sprayer was found to correctly detect and spray herbicides for weed control in soybean. The low amount of herbicide saved in 2023 can be directly linked to higher-than-normal weed infestation because no residual herbicide was applied during pre-plant herbicide application. In fields with minimal weed infestation, SS may allow producers to save high amounts of non-residual herbicides, as observed in 2022. A reduction in the use of non-residual herbicides has been directly linked to weed density, stage, and coverage in fallow and row-crop situations (Esau et al., 2018; Fischer et al., 2020). With this, herbicide savings could be roughly visually predicted pertaining to a field’s weed infestation and growth stage of weeds and crops. Similar level of weed control when using SS or broadcast are attractive and SS should be more rewarding in fields with low weed infestation. The sensitivity option may be adjusted per the operator's request to either increase weed detection or allow for more herbicide savings. With this, proper herbicide coverage is fundamental and should continue to be emphasized ahead of herbicide savings to reduce weed seed production.

The hope for herbicide savings through patch or site-specific application methods has been widely discussed (Donald et al., 2004; Luck et al., 2011; Miller, 2003). Buzanini et al. (2023) found that spot spray application techniques reduced non-residual herbicide use by 26% and 42% in the fall and spring in pepper production, with no significant effect on weed control or yield between target spray and broadcast. Furthermore, spot spraying may reduce herbicide runoff depending on the herbicide applied (Melland et al., 2016). These positive findings reaffirm that financial and environmental benefits are at play. Spot spray technology is being tested in wheat (Genna et al., 2021), in varying amounts of post-harvest stubble. Advances in other site-specific weed management allow for many options for weed control (Gerhards et al., 2022), opening the door for alternative weed control methods. The future of target spray technology is promising enough to further test this technology in various crops, cropping systems, and environments. Weather patterns, weed pressure, and cropping systems may impact this technology's benefit that should be considered by applicators to see if it fits their operation.

Literature Cited:

Anonymous (2024) Diflexx ® Herbicide label. Bayer Crop Science, Creve Couer, MO. https://www.cdms.net/ldat/ldC4D007.pdf

Anonymous (2022a) Harness Xtra® Herbicide label. Bayer Crop Science, Creve Couer, MO. https://www.cdms.net/ldat/ld0R1004.pdf

Anonymous (2022b) Sharpen ® Herbicide Label. BASF Agriculture. Research Triangle Park, NC. https://www.cdms.net/ldat/ld99E014.pdf

Anonymous (2021a) AAtrex ® Herbicide Label. Syngenta Crop Protection, Wilmington, DE. https://www.cdms.net/ldat/ld280014.pdf

Anonymous (2021b) Roundup PowerMax® Herbicide label. Bayer Crop Science, Creve Couer, MO. https://www.cdms.net/ldat/ld0RF009.pdf

Anonymous (2020a) Cobra® Herbicide Label. Valent USA LLC, San Ramon, CA. https://www.cdms.net/ldat/ld621002.pdf

Anonymous (2020b) Status ® Herbicide Label. BASF Agriculture. Research Triangle Park, NC. https://www.cdms.net/ldat/ld0K2017.pdf

Anonymous (2019). Liberty® Herbicide label. Research Triangle Park, NC: BASF. https://www.cdms.net/ldat/ldG9N002.pdf

Anonymous (2018). Enlist One® Herbicide Label. Corteva Agriscience, Indianapolis, IN https://www.greenbook.net/corteva-agriscience/enlist-one

Anonymous (2015) Callisto ® Herbicide label. Syngenta Crop Protection, Wilmington, DE. https://www.cdms.net/ldat/ld56N006.pdf

Barnhart, I. (2024). Use of artificial intelligence to locate and treat weeds in Midwestern United States corn (*Zea mays*) and soybean (*Glycine max*) cropping systems. *Kansas State Electronic Thesis*, 2004-2024. https://krex.k-state.edu/items/9781163b-79a9-4153-bf14-09a8b2a7d6dd/full

Buzanini, A.C., Schumann, A. & Boyd, N.S. (2024) Effects of pre-emergence herbicide on targeted post-emergence herbicide application in plasticulture production. *Precision Agric* (2024). https://doi.org/10.1007/s11119-024-10150-z

Buzanini, A. C., Schumann, A., & Boyd, N. S. (2023). Evaluation of smart spray technology for postemergence herbicide application in row middles of plasticulture production. *Weed Technology*, *37*(4), 336–342. https://doi.org/10.1017/wet.2023.44

Damalas, C. A., & Eleftherohorinos, I. G. (2011). Pesticide exposure, safety issues, and risk assessment indicators. *International Journal of Environmental Research and Public Health*, 8(5), 1402–1419. https://doi.org/10.3390/ijerph8051402

Deere and Company, Moline, IL. (2023). https://www.deere.com/en/sprayers/see-spray-ultimate/

Donald, W. W., Archer, D., Johnson, W. G., & Nelson, K. (2004). Zone herbicide application controls annual weeds and reduces residual herbicide use in corn. *Weed Science*, *52*(5), 821–833. https://doi.org/10.1614/WS-03-164R

Esau, T., Zaman, Q., Groulx, D., Farooque, A., Schumann, A., & Chang, Y. (2018). Machine vision smart sprayer for spot-application of agrochemical in wild blueberry fields. *Precision Agriculture*, *19*(4), 770–788. https://doi.org/10.1007/s11119-017-9557-y

Hussain N., Farooque A., Schumann A,, McKenzie-Gopsill A., Esau T., Abbas F., Acharya B., Zaman Q. 2020) Design and Development of a Smart Variable Rate Sprayer Using Deep Learning. *Remote Sensing*. 2020; 12(24):4091. https://doi.org/10.3390/rs12244091

Fischer, J. W., Thorne, M. E., & Lyon, D. J. (2020). Weed-sensing technology modifies fallow control of rush skeletonweed (Chondrilla juncea). *Weed Technology*, *34*(6), 857–862. https://doi.org/10.1017/wet.2020.76

Fischer, T. (2023). Personal communication, Nov. 2, 2023.

Gammon, D. W., Aldous, C. N., Carr, W. C. J., Sanborn, J. R., & Pfeifer, K. F. (2005). Risk assessment of atrazine use in California: human health and ecological aspects. *Pest Management Science*, *61*(4), 331–355. https://doi.org/10.1002/ps.1000

Gerhards, R., Andújar Sanchez, D., Hamouz, P., Peteinatos, G. G., Christensen, S., & Fernandez-Quintanilla, C. (2022). Advances in site-specific weed management in agriculture—A review. *Weed Research*, *62*(2), 123–133. https://doi.org/10.1111/wre.12526

Genna, N.G., Gourlie, J.A., Barroso, J. (2021). Herbicide Efficacy of Spot Spraying Systems in Fallow and Postharvest in the Pacific Northwest Dryland Wheat Production Region. *Plants* 2021, *10*, 2725. https://doi.org/10.3390/plants10122725

Gonzalez-de-Soto, M., Emmi, L., Perez-Ruiz, M., Aguera, J., & Gonzalez-de-Santos, P. (2016). Autonomous systems for precise spraying–Evaluation of a robotised patch sprayer. *Biosystems engineering*, *146*, 165-182. https://doi.org/10.1016/j.biosystemseng.2015.12.018

Greogry, E, Leach, Macy. (2022) 2018-2022 Crop Input Expense Summary. Mississippi State Extension, pub. 3758, (2022). https://extension.msstate.edu/publications/2018%E2%80%9322-crop-input-expense-summary

Hamouz, P., Hamouzová, K., & Novotná, K. (2015). Effects of spring herbicide treatments on winter wheat growth and grain yield. *Scientia agriculturae bohemica*, *46*(1), 1-6. doi: 10.1515/sab-2015-0010

Jin X., Liu T., Yang Z., Xie J., Bagavathiannan M., Hong X., Xu Z., Chen X., Yu J., Chen Y. (2023). Precision weed control using a smart sprayer in dormant bermudagrass turf. *Crop Protection*, *Volume 172*, 2023, 106302, https://doi.org/10.1016/j.cropro.2023.106302.

Jin, X., McCullough, P. E., Liu, T., Yang, D., Zhu, W., Chen, Y., & Yu, J. (2023). A smart sprayer for weed control in bermudagrass turf based on the herbicide weed control spectrum. *Crop Protection*, *170*, 106270. https://doi.org/10.1016/j.cropro.2023.106270

Kouame, K. B. J., Butts, T. R., Norsworthy, J. K., Davis, J., & Piveta, L. B. (2023). Palmer amaranth Amaranthus palmeri) control affected by weed size and herbicide spray solution with nozzle type pairings. *Weed Technology*, *38*, 1–9. https://doi.org/10.1017/wet.2023.92

Kumar, V., & Jha, P. (2015). Effective Preemergence and Postemergence Herbicide Programs for Kochia Control. *Weed Technology*, *29*(1), 24–34. https://doi.org/10.1614/WT-D-14-00026.1

Lerro, C. C., Hofmann, J. N., Andreotti, G., Koutros, S., Parks, C. G., Blair, A., Beane Freeman, L. E. 2020). Dicamba use and cancer incidence in the agricultural health study: an updated analysis *International Journal of Epidemiology*, *49*(4), 1326–1337. https://doi.org/10.1093/ije/dyaa066

Luck, J. D., Pitla, S. K., Zandonadi, R. S., Sama, M. P., & Shearer, S. A. (2011). Estimating off-rate pesticide application errors resulting from agricultural sprayer turning movements. *Precision Agriculture*, *12*, 534-545. https://doi.org/10.1007/s11119-010-9199-9

Lyon, D. J., Miller, S. D., & Wicks, G. A. (1996). The future of herbicides in weed control systems of the Great Plains. *Journal of Production Agriculture*, *9*(2), 209-215. https://doi.org/10.2134/jpa1996.0209

Matthews, G. A., Bateman, R., Miller, P., & Thompson, S. (2014). *Pesticide Application Methods* (Fourth edition.). Book Chapter. Wiley-Blackwell.

Melland, A. R., Silburn, D. M., McHugh, A. D., Fillols, E., Rojas-Ponce, S., Baillie, C., & Lewis, S. 2016). Spot spraying reduces herbicide concentrations in runoff. *Journal of agricultural and food chemistry*, *64*(20), 4009-4020. https://doi.org/10.1021/acs.jafc.5b03688

Miller, P. C. (2003). Patch spraying: future role of electronics in limiting pesticide use. *Pest Management Science*, *59*(5), 566-574. https://doi-org.libproxy.unl.edu/10.1002/ps.653

Meyer, C. J., & Norsworthy, J. K. (2019). Influence of weed size on herbicide interactions for Enlist™ and Roundup Ready® Xtend® technologies. *Weed Technology*, *33*(4), 569–577. https://doi.org/10.1017/wet.2019.27

Pacanoski, Z. (2007). Herbicide use: benefits for society as a whole-a review. *Cabidigitallibrary*, Vol. 13, No. 1/2, 135-147. https://www.cabidigitallibrary.org/doi/full/10.5555/20083050759

Partel, V., Kakarla, S. C., & Ampatzidis, Y. (2019). Development and evaluation of a low-cost and smart technology for precision weed management utilizing artificial intelligence. *Computers and electronics in agriculture*, *157*, 339-350. https://doi.org/10.1016/j.compag.2018.12.048

Sapkota, M., Virk, S., & Rains, G. (2023). Spray Deposition and Quality Assessment at Varying Ground Speeds for an Agricultural Sprayer with and without a Rate Controller. *AgriEngineering*, *5*(1), 506–519. https://doi.org/10.3390/agriengineering5010033

Staff, ASABE. (2022). See & Spray TM Select by John Deere. *Resource Magazine*, *29*(3), 7-8. https://elibrary.asabe.org/abstract.asp?aid=53257

Spaeth, M., Sökefeld, M., Schwaderer, P., Gauer, M. E., Sturm, D. J., Delatrée, C. C., & Gerhards, R. 2024). Smart sprayer a technology for site-specific herbicide application. *Crop Protection*, *177*, 106564. https://doi.org/10.1016/j.cropro.2023.106564

Sousa Alves, G., Kruger, G. R., da Cunha, J. P. A. R., de Santana, D. G., Pinto, L. A. T., Guimarães, F., & Zaric, M. (2017). Dicamba Spray Drift as Influenced by Wind Speed and Nozzle Type. *Weed Technology*, *31*(5), 724–731. doi:10.1017/wet.2017.61

Tonks, D. J., & Westra, P. (1997). Control of sulfonylurea-resistant kochia (Kochia scoparia). *Weed Technology*, *11*(2), 270–276. https://doi.org/10.1017/s0890037x00042949

Werle, R., Mobli, A., Striegel, S., Arneson, N., DeWerff, R., Brown, A., & Oliveira, M. (2022). Large-scale evaluation of 2,4-D choline off-target movement and injury in 2,4-D-susceptible soybean. *Weed Technology*, *36*(1), 8–14. https://doi.org/10.1017/wet.2021.62

Wicks, G. A., Martin, A. R., & Hanson, G. E. (1997). Controlling kochia (Kochia scoparia) in soybean Glycine max) with postemergence herbicides. *Weed Technology*, *11*(3), 567–572. https://doi.org/10.1017/s0890037x00045437

Wolf, R., Clay, S. A., & Wrage, L. J. (2000). Herbicide Strategies for Managing Kochia (Kochia scoparia) Resistant to ALS-Inhibiting Herbicides in Wheat (Triticum aestivum) and Soybean Glycine max). *Weed Technology*, *14*(2), 268–273. https://doi.org/10.1614/0890-037

Yarpuz-Bozdogan, N. (2018). The importance of personal protective equipment in pesticide applications in agriculture. *Current Opinion in Environmental Science & Health*, *4*, 1–4. https://doi.org/10.1016/j.coesh.2018.02.001

Villette, S., Maillot, T., Guillemin, J.-P., & Douzals, J.-P. (2022). Assessment of nozzle control strategies in weed spot spraying to reduce herbicide use and avoid under- or over-application. *Biosystems Engineering*, *219*, 68–84. https://doi.org/10.1016/j.biosystemseng.2022.04.012

Vogt, W. (2022). John Deere rolls out See Spray Ultimate. In *Farm Progress*. Penton Media, Inc., Penton Business Media, Inc. and their subsidiaries. https://www.farmprogress.com/farming-equipment/john-deere-rolls-out-see-spray-ultimate

Yu, Jialin, et al. (2019). Detection of Broadleaf Weeds Growing in Turfgrass with Convolutional Neural Networks. *Pest Management Science*, vol. 75, no. 8, 2019, pp. 2211–18, https://doi.org/10.1002/ps.5349.

Zanin, A. R. A., Neves, D. C., Teodoro, L. P. R., da Silva Júnior, C. A., da Silva, S. P., Teodoro, P. E., & Baio, F. H. R. (2022). Reduction of pesticide application via real-time precision spraying. *Scientific Reports*, *12*(1), 5638. https://doi.org/10.1038/s41598-022-09607-w

Table 1: Herbicides, application rates, trade names, and application techniques used in a field study conducted for weed control in corn with Greeneye Technology's precision sprayer near Clay Center, Nebraska, USA in 2022 in early-POST (EPOST) and late-POST (LPOST) application timings.

Application Timing	Tank 1 Herbicide	Tank 1 Rate	Tank 1 Trade Name[a]	Tank 2 Herbicide	Tank 2 Rate	Tank 2 Trade[a] Name
		g ai ha^{-1}			g ai ha^{-1}	
EPOST	Acetochlor/atrazine + mesotrione	4,033 + 165	Harness Xtra + Callisto	Dicamba + glyphosate	350 + 945	DiFlexx + Roundup PowerMax
LPOST	acetochlor/atrazine + atrazine + mesotrione	1,344 + 488 + 105	Harness Xtra + AAtrex 4L + Callisto	Dicamba/diflufenzopyr + glyphosate	196 + 945	Status + Roundup PowerMax

Treatment	Tank 1 Application Technique	Tank 2 Application Technique
1	Broadcast	N/A
2	Broadcast	Spot
3	Broadcast	Broadcast

[a]Manufacturer: Harness Xtra, Bayer Crop Science, Creve Couer, MO; Callisto, Syngenta Crop Protection, Wilmington, DE; AAtrex 4L, Syngenta Crop Protection; Diflexx, Bayer Crop Science; Roundup PowerMax, Bayer Crop Science; Status, BASF Agriculture, Research Triangle Park, NC.

Table 2: Herbicides, rates, and trade names in a field study conducted for weed management in soybean with John Deere' precision sprayer near Mead, Nebraska in 2023. Each treatment was applied as broadcast and spot (target) spray separately in early-POST (EPOST) and late-POST (LPOST) applications.

Herbicide[a]	Timing[a]	Rate (g ai/ae ha^{-1})[a]	Trade Name	Manufacturer[a,b]
2,4-D choline fb glufosinate	EPOST fb LPOST	1,284 fb 881	Enlist One fb Liberty	Corteva fb BASF

glyphosate fb lactofen	EPOST fb LPOST	1,091 fb 168	Roundup PowerMax fb Cobra	Bayer fb Valent
glufosinate fb glyphosate	EPOST fb LPOST	655 fb 1,091	Liberty fb Roundup PowerMax	BASF fb Bayer
saflufenacil fb 2,4-D choline	EPOST fb LPOST	21 fb 1,284	Sharpen fb Enlist One	BASF fb Corteva

[a]Abbreviations; fb, followed by; ai, active ingredient; ae, acid equivalent.
[b] Corteva Agriscience, Indianapolis, IN; BASF Corporation Research Triangle Park, NC; Bayer CropScience, Creve Coeur, MO; Valent USA Corporation, San Ramon, CA.

Table 3: Palmer amaranth and giant foxtail control at 7, 14, and 21 d after treatment (DAT) of LPOST in a field study conducted for weed control in corn with Greeneye Technology's precision sprayer near Clay Center, Nebraska, USA in 2022.

	Percent control					
	7 DAT		14 DAT		21 DAT	
Application Technique	Palmer amaranth[a]	giant foxtail[a]	Palmer amaranth[a]	giant foxtail[a]	Palmer amaranth[a]	giant foxtail[a]
Broadcast	97 a	92 a	94 a	80 b	93 b	77 b
Broadcast + Spot	99 a	93 a	99 a	90 ab	99 a	94 a
Broadcast + Broadcast	98 a	99 a	99 a	99 a	99 a	99 a
P- value	.18	.23	.15	.07	.04	.01

[a]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at P ≤ 0.05.

Table 4: Common lambsquarters, kochia, and waterhemp control at 7, 14, and 21 d after treatment (DAT) of early-POST herbicides (EPOST) in a field study conducted for weed management in soybean with John Deere' precision sprayer near Mead, Nebraska in 2023.

.

Herbicide	**A.T[a].**	common lambsquarters[b]			kochia[b]			waterhemp[b]		
		7 DAT	14 DAT	21 DAT	7 DAT	14 DAT	21 DAT	7 DAT	14 DAT	21 DAT
		--% control-- ---								

2,4-D choline	Broadcast	85 b	84 a	83 b	41 d	31 b	30 b	79 c	78 b	77 c
2,4-D choline	Spot Spray	85 b	90 a	89 ab	16 e	38 b	34 b	81 bc	80 b	79 bc
glyphosate	Broadcast	97 a	97 a	96 a	98 a	97 a	97 a	94 a	96 a	93 ab
glyphosate	Spot Spray	95 ab	97 a	97 a	99 a	98 a	98 a	95 a	97 a	97 a
glufosinate	Broadcast	45 c	36 b	36 c	74 bc	48 b	50 b	92 ab	96 a	94 ab
glufosinate	Spot Spray	42 c	33 b	29 c	62 c	47 b	49 b	95 a	96 a	95 a
saflufenacil	Broadcast	96 a	94 a	93 ab	92a b	96 a	95 a	98 a	99 a	99 a
saflufenacil	Spot Spray	95 ab	91 a	91 ab	92 ab	96 a	94 a	98 a	99 a	99 a
P-value		.0001	.0001	.0001	.0001	.0001	.0001	.018	.0029	.014
Broadcast vs. Spot Spray[c]		81 vs 79	78 vs 77	77 vs 76	76 vs 67	68 vs 70	67 vs 69	91 vs 92	92 vs 93	91 vs 92

[a]Abbreviations: A.T., Application Technique.

[b]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at p ≤ 0.05

[c]Asterisks (*) indicate a significant difference between broadcast and spot spray contrast means at P<0.1.

Table 5: Common lambsquarters, kochia, and waterhemp control at 7, 14, and 21 d after treatment (DAT) of late-POST (LPOST) herbicides in a field study conducted for weed management in soybean with John Deere' precision sprayer near Mead, Nebraska in 2023.

		Common lambsquarters[a]			Kochia[a]			Waterhemp[a]		
Herbicide	**Application Technique**	7 DAT	14 DAT	21 DAT	7 DAT	14 DAT	21 DAT	7 DAT	14 DAT	21 DAT
		----------% control----------								
glufosinate	Broadcast	98 a	96 a	53 b	99 a	98 a	99 a	99 a	96 ab	53 b
glufosinate	Spot Spray	98 a	96 a	53 b	99 a	97 a	99 a	99 a	99 a	53 b
lactofen	Broadcast	64 b	77 b	49 b	99 a	71 b	93 b	95 a	91 c	49 b

lactofen	Spot Spray	64 b	77 b	64 b	99 a	62 c	94 ab	86 b	96 ab	64 b
glyphosate	Broadcast	99 a	99 a	99 a	99 a	9 5a	98 ab	93 ab	98 ab	99 a
glyphosate	Spot Spray	99 a	99 a	97 a	98 a	96 a	98 ab	96 a	95 bc	97 a
2,4-D choline	Broadcast	98 a	99 a	98 a	98 a	98 a	96 ab	98 a	96 ab	98 a
2,4-D choline	Spot Spray	96 a	99 a	99 a	95 b	93 a	99 a	99 a	97 ab	99 a
P-value		.0001	.0001	.0001	.0001	.0001	0.25	.09	.0045	0.61
Broadcast vs. Spot Spray[b]		90 vs 89	93 vs 93	75 vs 78	99 vs 98	91 vs 87	97 vs 98	96 vs 95	95 vs 97	75 vs 78*

[a]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $p \leq 0.05$.
[b]Asterisks (*) indicate a significant difference between broadcast and spot spray contrast means at $P<0.1$.

Table 6: Palmer amaranth and giant foxtail density (plants m^{-2}) as affected by herbicide application techniques at 7, 14, and 21 d after treatment (DAT) of late-POST (LPOST) herbicides in a field study conducted for weed control in corn with Greeneye Technology's precision sprayer near Clay Center, Nebraska, USA in 2022.

Application Technique	7 DAT[a]		14 DAT[a]		21 DAT[a]	
	Palmer amaranth	Giant foxtail	Palmer amaranth	Giant foxtail	Palmer amaranth	Giant foxtail
	plants m^{-2}					
Broadcast	0.2 a	0.2 a	0.2 a	1.5 a	0.3 a	2.3 a
Broadcast + Spot	0 a	0.1 a	0 a	0.7 ab	0 a	0.3 b
Broadcast + Broadcast	0 a	0 a	0 a	0 b	0 a	0 b
P-value	0.38	0.23	0.42	0.04	0.24	0.03

[a]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 7: Broadcast vs spot spray contrast for weed density (plants m^{-2}) at 14 d after treatment (DAT) of early-POST (EPOST) and 14 d after treatment (DAT) of late-POST (LPOST) separated by species in spot spray trial conducted in soybean with John Deere' See and Spray technology near Mead, NE in 2023.

Weed	14 DAT[a,b,c]	14 DAT[a,b,c]

	EPOST	LPOST
	----------------plants m^{-2}--------------	
Common lambsquarters	1.4 vs 1.0*	0.8 vs 1.0
Kochia	3.1 vs 2.4	0.6 vs 0.3
Waterhemp	0.3 vs 0.4	0.7 vs 0.9

[a] DAT, Days after treatment.
[b] Asterisks (*) indicate a significant difference between broadcast and spot spray contrast means at P<0.1.
[c] Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at P ≤ 0.05.

Table 8: Percent of acreage covered with non-residual herbicide applied using Tank 2 of Greeneye technology in early-POST (EPOST) applications and late-POST (LPOST) in spot spray trial conducted in corn near Clay Center, NE in 2022.

Tank 1[a]	Tank 2[b]	Timing	Tank 2 % area covered[c]	% Herbicide Savings
Broadcast	N/A	EPOST fb LPOST	0 fb 0	--
Broadcast	Spot	EPOST fbLPOST	6 fb 13	94% fb 87%
Broadcast	Broadcast	EPOST fb LPOST	100 fb 100	0%

[a]Tank 1 included herbicide with residual activity.
[b]Tank 2 included herbicides with non-residual activity.
[c]Herbicide applied on a scale of 0-100%, with 100% indicating spot spray was activated the entire application. Fb means followed by.

Table 9: Herbicide savings and percent area covered compiled using John Deere' See and Spray technology in early-POST (EPOST) and late-POST (LPOST) applications in trials conducted in soybean near Mead, NE in 2023.

Herbicide[a]	Timing[a]	Rate (g ai/ae ha^{-1})[a]	% area covered[ab]	% herbicide savings[ab*]
2,4-D choline fb glufosinate	EPOST fb LPOST	1,284 fb 881	98.9 fb 100	1.1 fb 0

glyphosate fb lactofen	EPOST fb LPOST	1,091 fb 128	94.6 fb 100	5.4 fb 0
glufosinate fb glyphosate	EPOST fb LPOST	655 fb 1,091	96.8 fb 100	3.2 fb 0
saflufenacil fb 2,4-D choline	EPOST fb LPOST	21 fb 1,284	98.1 fb 100	1.9 fb 0

[a]Abbreviations; fb; followed by, ai; active ingredient, ae: acid equivalent.
[b]Herbicide applied on a scale of 0-100%, with 100% indicating spot spray was activated the entire application.
*Residual herbicide was not applied in EPOST application.

Figure 1. Greeneye technology machine used in spot spray trial conducted in corn near Clay Center, NE in 2022. This system can be retrofitted on compatible sprayers.

Figure 2. John Deere' See and Spray machine with boom a) folded and b) unfolded (37 m wide boom) before A application in spot spray trial conducted in soybean near Mead, NE in 2023.

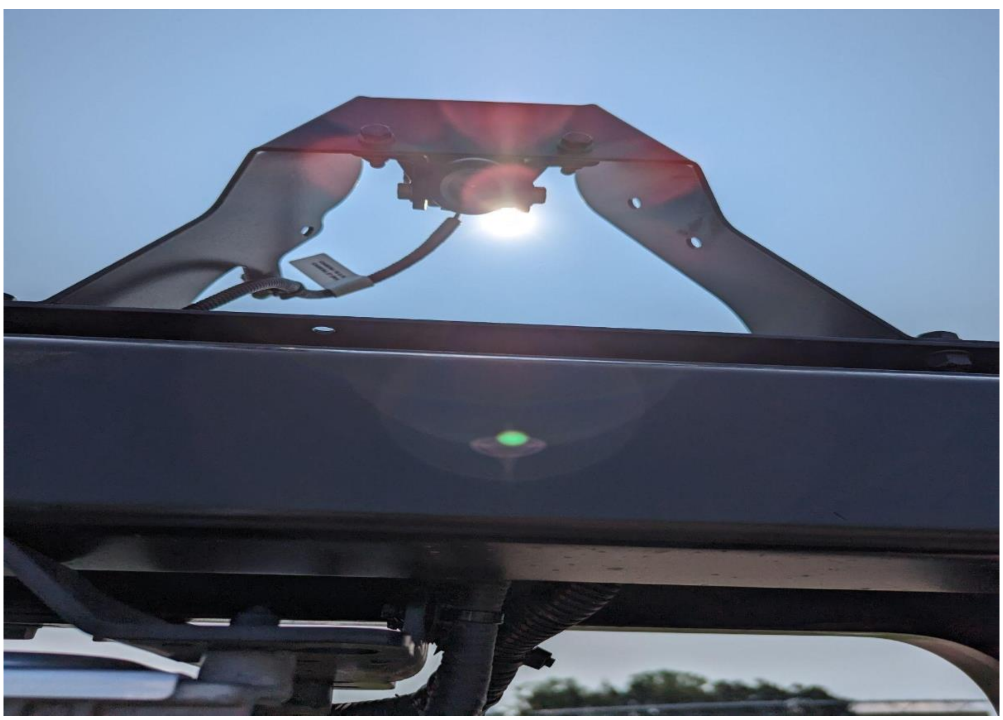

Figure 3. One of 36 cameras attached to boom of John Deere See and Spray used in spot spray trials conducted near Mead, NE in 2023.

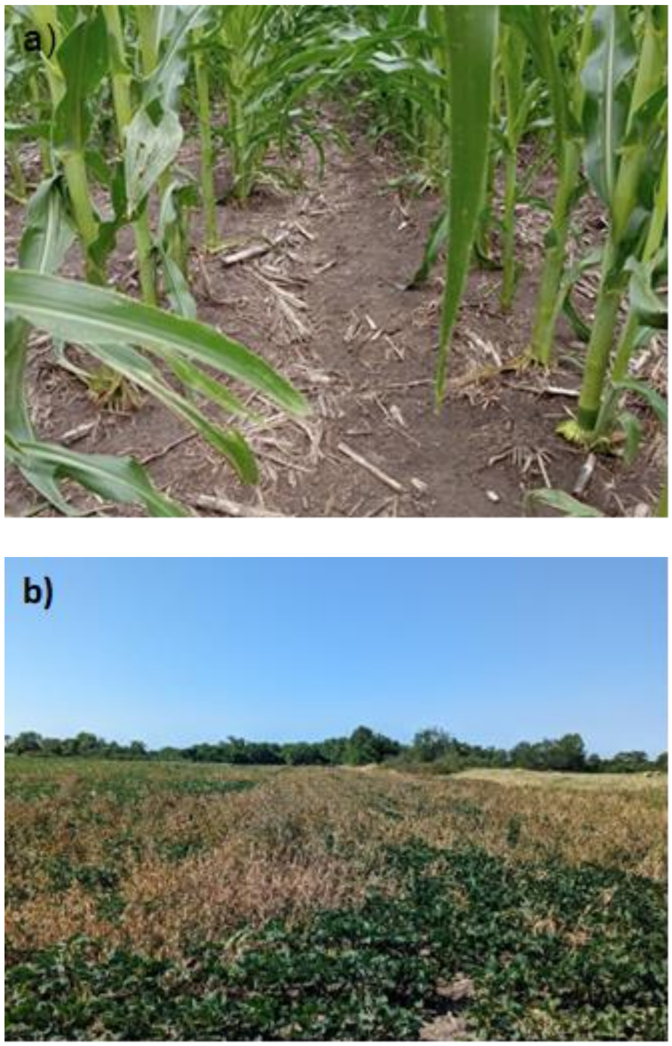

Figure 4. Low weed pressure as depicted in between corn rows 21 d after LPOST in an experimental field in Greeneye's Spot Spray trial conducted near Clay Center, NE in 2022, and high weed pressure as depicted by injured weed plants 7 d after LPOST in an experimental field in John Deere' See and Spray trial conducted near Mead, NE in 2023.

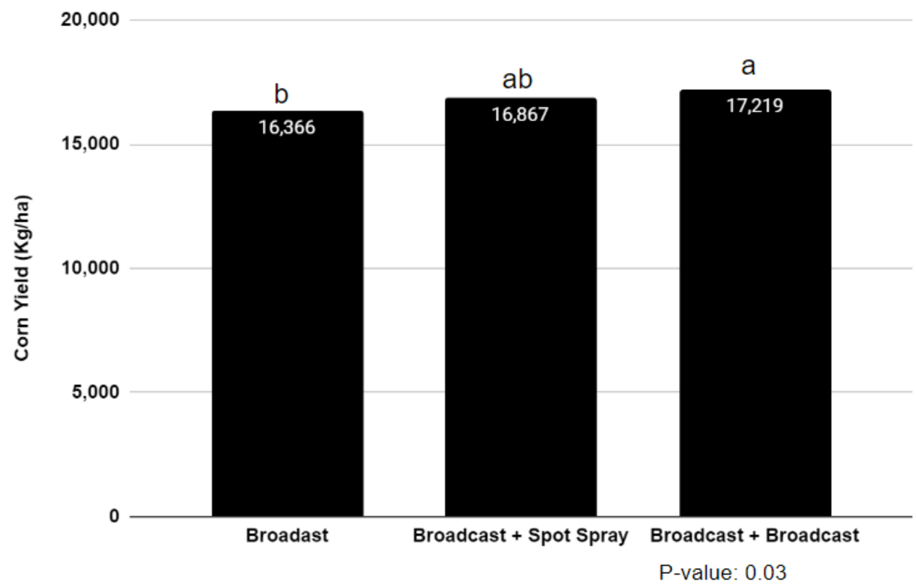

Figure 5: Corn yield as affected by application techniques in a Greeneye technology spot spray trial conducted near Clay Center, NE in 2022.

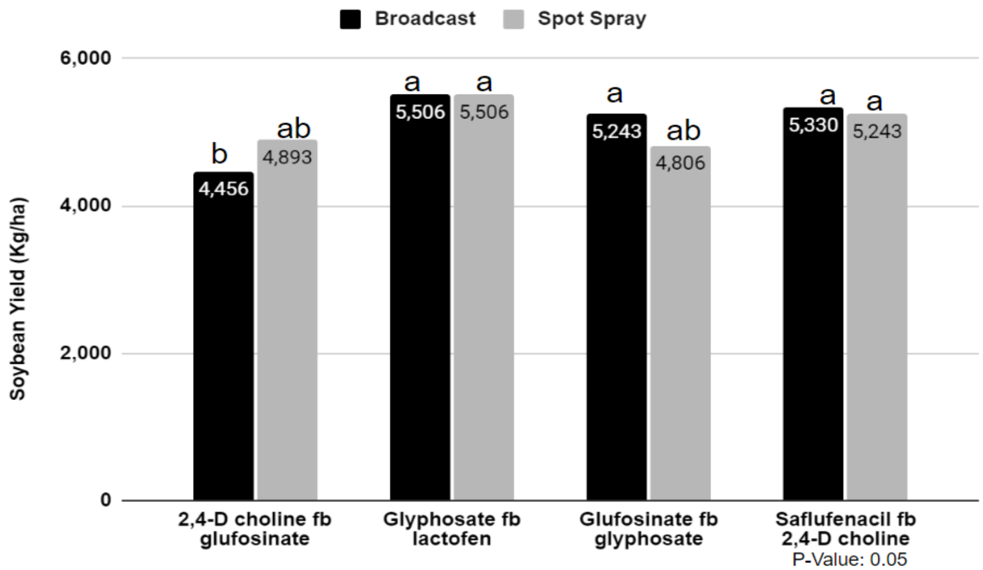

Figure 6: Soybean yield as affected by application techniques and herbicide programs in a John Deere' See and Spray field trial conducted near Mead, NE in 2023.

A precision dual tank sprayer to overcome antagonism of mixing dicamba and clethodim for control of glufosinate/glyphosate-resistant corn volunteers in dicamba-resistant soybean

Adam Leise

ABSTRACT

Clethodim is mixed with dicamba for control of volunteer corn in dicamba-resistant soybean. However, this mixture is often antagonistic, reducing the efficacy of clethodim for control of volunteer corn. John Deere's new precision sprayer with dual tank can reduce antagonism because two herbicides can be applied simultaneously through separate nozzles. The objective of this study was to evaluate the dual tank option of precision sprayer for control of glufosinate/glyphosate-resistant volunteer corn in soybean with dicamba and clethodim applied from the same tank or dual tank. A field experiment was conducted in 2023 in southcentral Nebraska. Bin-run glufosinate/glyphosate-resistant corn was planted at 54,000 seeds ha^{-1} to mimic as volunteer corn in dicamba-resistant soybean. Clethodim (54 and 76 g ai ha^{-1}) and dicamba (558 g ae ha^{-1}) were applied as tank mix (mixed in the same tank) and dual tank (separate tank) application technique. Clethodim at 54 and 76 g ai ha^{-1} provided 90% and 94% volunteer corn control 28 days after application (DAA), respectively. Mixing clethodim at 54 and 76 g ai ha^{-1} with dicamba in the same tank resulted in 21% and 28% volunteer corn control, respectively. Clethodim and dicamba applied in dual; tank (separate tank) provided similar control (97%-99%) as clethodim applied alone and 71%-76% higher control compared to tank mix application. It is concluded that precision sprayer with dual tank system is effective to overcome antagonism of mixing clethodim and dicamba in the same tank for control of volunteer corn in soybean.

INTRODUCTION

Soybean is one of the major crops in the United States with production of 113 million MT in 2023 (USDA, 2024). In the Midwestern United States, corn-soybean rotation continues to be a popular choice among growers due to its known benefits including flexibility in rotating herbicide modes of action and lower pest pressure (Sexton 2019). In this rotation, corn kernels or ears lost during the previous year due to harvest inefficiency or adverse weather may overwinter and emerge as volunteer corn the following spring (Chahal & Jhala, 2015). This presents a challenge for optimal soybean production. Volunteer corn in soybeans is a problem weed that can affect soybean yield (Alms et al., 2016). Research in Nebraska has found that volunteer corn at a density of 10,000 plants ha^{-1} reduced soybean yield by 22% compared to no volunteer corn (Chahal & Jhala, 2015). Nearby, studies in South Dakota have shown that when volunteer corn density reaches one plant per 0.9 m^{-2}, soybean yield was decreased by 8-9% (Rosenberg & Deneke, 2020).

The introduction of herbicide-resistant (HR) crops has added cropping choices for growers that have expanded herbicide options for weed control. Since their introduction, growers have been quick to adopt HR crops in their farming operations (Reddy & Nandula, 2012). as the adoption of HR crops is one of the fastest adoptions in agriculture history (Green & Siehl, 2021). With this adoption, HR weeds such as glyphosate-resistant weeds have been on the rise since the commercial cultivation of glyphosate-resistant crops (Beckie et al., 2006; Clay, 2021; Roma-Burgos et al., 2018;). The evolution of HR weeds and their widespread occurrence resulted in in stacking HR traits into corn and soybean to allow herbicide options for control of HR weeds (Ceccon et al., 2020; Dill et al., 2008). With the commercial cultivation of multiple HR traits in corn and soybean, it is challenging to control multiple HR crop volunteers in the following growing season, specifically volunteer corn (Jhala et al. 2022). Soil-applied residual herbicides labeled for grass control in soybean are available in the market, but research has shown that these herbicides provide poor control of HR volunteer corn (Chahal & Jhala, 2015). If this issue arises, HR volunteer corn needs to be managed through the POST herbicides. Volunteer corn resistant to glufosinate and glyphosate may need graminicide (grass herbicide) such as clethodim, quizalofop-p-ethyl, sethoxydim, among others to provide effective control in soybean (Jhala and Rees, 2018). ACCase-inhibiting herbicides, which includes the FOP, DIM, and DEN families, are effective in controlling specifically monocot plants due to their ability to inhibit the homomeric plastidic ACCase gene, halting this formation by blocking fatty acid biosynthesis (Takano et al., 2020). Symptoms of ACCase-inhibiting herbicides include chlorotic or bleaching of leaves at lower concentrations, with higher concentrations leading to a killed growing point and rotten whorl (Butts et al., 2023).

Soybean resistant to dicamba/glufosinate/glyphosate (XtendFlex soybean Bayer Crop Science, Creve Coeur, MO) were commercialized in (Anonymous, 2020) which provides the option to use dicamba for broadleaf weed control. Oftentimes, when broadleaf weeds such as Palmer amaranth and waterhemp along with volunteer corn are present in soybean fields in Nebraska and several other states in the Midwest where soybean is typically grown in rotation with corn. When growers mix graminicides such as clethodim for glufosinate/glyphosate-resistant volunteer corn control and dicamba for broadleaf weed control, clethodim has been reported to exhibit a reduced efficacy providing less than expected volunteer corn control (Perkins et al., 2021; Underwood et al., 2016), resulting in ineffective volunteer corn control with a POST application. While a single application of herbicide mixture is desirable for growers for saving time and financial incentives, the separate application of clethodim and dicamba is more appropriate due to antagonistic interaction.

John Deere (Deere and Company, Moline, IL, USA) has developed a new precision sprayer (Figure 1) equipped with a dual tank system that allows for simultaneous herbicide applications from separate tanks and nozzles (John Deere, 2023). This system allows for the herbicides to be entirely separated from tank to tip until they reach the plant. The use of a dual tank system may reduce or overcome herbicide antagonism that otherwise occurs when mixed in the same tank. Scientific literature is lacking on whether dual tank systems can reduce the antagonistic effect of clethodim + dicamba by maintaining clethodim's efficacy for controlling volunteer corn. The objective of this study was to evaluate efficacy of clethodim applied in a separate tank (dual tank) using the precision dual tank sprayer or mixed with dicamba in the same tank (tank-mix) for control of glufosinate/glyphosate-resistant corn volunteers in dicamba/glufosinate/glyphosate-resistant soybean. We hypothesized that utilizing the dual tank system could decrease the antagonistic effect of dicamba on clethodim, thus increasing clethodim's efficacy for controlling glyphosate/glufosinate-resistant corn volunteers.

MATERIALS & METHODS

2.1 Experimental site and design, and agronomic management

The field experiment was conducted in 2023 at the University of Nebraska-Lincoln's South-Central Agricultural Laboratory near Clay Center, NE (40.58, -98.14). The experimental field was under a no-till production system and rainfed conditions. The experiment was arranged in a randomized complete block design with 2 replications and 4 pseudo-replicates in each. Plot size was 18 m wide by 46 m long. A large plot size was preferred for ease of application and sprayer coordination as the sprayer width was 37 m with the capacity to apply herbicide on a minimum of 18 m. Dicamba/glufosinate/glyphosate-resistant soybean (XtendFlex soybean; NK-J9XF; NK Seeds, Hopkins, MN) was planted at 308,750 seeds ha^{-1} on May 11, 2023. After planting soybean, bin-run glufosinate/glyphosate-resistant corn seeds were planted at 54,000 seeds ha^{-1} using a circular spreader and incorporated using a cultivator on the same day. A preemergence (PRE) application of pyroxasulfone (Zidua SC; BASF Agriculture, Research Triangle Park, NC, USA) at 120 g ai ha^{-1} and glufosinate (Liberty; BASF Agriculture, Research Triangle Park, NC, USA) at 593 g ai ha^{-1} was applied on May 16. Neither soybean nor volunteer corn had emerged at the time of PRE herbicide application.

2.2 Herbicide treatments

Clethodim (Select Max, Valent USA, San Ramon, CA, USA) rates at 54 and 76 g ai ha^{-1} were chosen for controlling glufosinate/glyphosate-resistant volunteer corn and referred to as a 'lower rate' and a 'higher rate', respectively (Anonymous 2020). Herbicide treatments consisted of clethodim at 54 and 76 g ai ha^{-1}, dicamba at 558 g ae ha^{-1}, clethodim at 54 and 76 g ai ha^{-1}

mixed with dicamba, and applied in a separate tank using the dual tank system through separate nozzles or mixed in the same tank and applied through a single nozzle (Table 1). In total, seven herbicide treatments were applied on June 15. When herbicides were applied, volunteer corn was between the V5-V6 growth stage. Treatments containing dicamba included VaporGrip Xtra Agent (Verified; Helena Agri-Enterprises, Collierville, TN) at 1,449 ml ha^{-1} and a drift reduction agent (Interlock; Winfield United, Arden Hills, MN) at 0.5% v/v. AIXR 11015 coarse droplet flat fan nozzles (TeeJet Technologies; Glendale Heights, IL) were used for clethodim application, and TTI 110015 (TeeJet Technologies) extremely coarse droplet nozzles were used for treatments containing dicamba, with a spray rate of 187 L ha^{-1} at 276 kPa. During the time of application, the temperature was 30°C with a wind speed of 8-16 km h^{-1}. The speed of the sprayer was 13 km h^{-1}.

2.3 Machine design

The John Deere (Deere and Company, Moline, IL) 612R sprayer equipped with a dual tank system was used for this experiment. This model is equipped with a boom length of 37 m, which includes 36 cameras and 96 nozzles spaced 38 cm apart. The dual tank system, the study's focus, is equipped with tanks A and B with separate flow lines. This system keeps the herbicides in both tanks separate from ‘tip to tank’ to keep the active ingredients separate during application. Tank A has a 2,839 L capacity, compared to tank B’s 1,703 L capacity. John Deere recommends that Tank B is preferred to be used for See and Spray™ (target) application of non-residual herbicides, while Tank A is preferred for blanket application of residual herbicides. The boom height is preferred to be between 26-48 cm above the ground or canopy, with a boom height of 30 cm for this project at the time of herbicide application. The See and Spray™ feature was equipped on this model but was not activated during application because clethodim and dicamba were applied broadcast to evaluate their interaction.

2.4 Data collection and analysis

Visual estimates of volunteer corn control were determined at 7, 14, 21, and 28 days after application (DAA) on a scale of 0% to 100% where 0% indicates volunteer corn with no injury and 100% indicates complete control. Volunteer corn density was determined by counting plants in two one m^2 quadrats side by side, in a random and representative area of the plot at 14 and 28 DAA. Soybean injury was assessed at 14 and 28 DAA to determine phytotoxicity damage- with 0% indicating no damage from herbicide and 100% indicating complete plant death due to herbicide injury. At maturity, soybean was harvested using a John Deere 9570 combine, and yield data were categorized using ArcGIS PRO version 3.2 (Ersi GIS Mapping Systems, Redlands, CA).

Antagonism occurs when the mixture of herbicides leads to less control than the herbicide applied individually (Colby, 1967). Colby (1967) further developed a mathematical equation to calculate the expected control from two or more herbicides applied in a mixture.

$$E= (X+Y)-XY/100$$

where X is the percent control of volunteer corn with herbicide A, Y is the percent control with herbicide B, and E is the expected control with a mixture of A and B herbicides. The expected means of treatments containing clethodim plus dicamba were calculated and compared against the observed control using a *t*-test with significance at $\alpha= 0.05$ (Singh et al., 2023). Data were analyzed in SAS studio (9.4) using the PROC GLIMMIX package. Block was deemed a random effects, while herbicide treatments were used as a fixed effect. Type III fixed effect tests were used to assess fixed effects differences and treatment means were separated using LSMEANS with Tukey's test at α= 0.05.

RESULTS AND DISCUSSION

Volunteer corn control

Clethodim 54 and 76 g ai ha^{-1} provided 79% and 84% control of volunteer corn 7 DAA, respectively (Table 2). Striegel et al. (2020) found that clethodim at 68 g ai ha$^{–1}$ provided 94% control of volunteer corn 14 days after POST (DAP) and 90% control at 28 DAP. Furthermore, Soltani et al. (2015) observed that clethodim as low as 30 g ai ha$^{–1}$ can control 88% of volunteer corn 14 DAP, and 92% of volunteer corn 28 DAP. Thus, selected rates of 54 and 76 g ai ha$^{–1}$ were effective for controlling volunteer corn. When clethodim at 54 and 76 g ai ha$^{–1}$ was applied with dicamba 558 g ae ha$^{–1}$ using a dual tank, volunteer corn control was 49% and 84%, compared with 28% and 30% control when mixed in the same tank, respectively. Colby's analysis indicated antagonistic interaction when clethodim at 54 and 76 g ai ha$^{–1}$ was mixed with dicamba in the same tank– providing 51% and 54% less than the expected control of 79% and 84%), respectively. However, dual tank applications were not antagonistic; for example, observed volunteer corn control with the higher rate of clethodim (76 g ai ha$^{–1}$) was the same as expected (84%). At 21 DAA, clethodim at 54 and 76 g ai ha$^{–1}$ provided 94% and 99% control when applied using a dual tank system with dicamba, which was 78% and 69% higher than mixing clethodim and dicamba in a single tank, respectively (Figure 2). The observed control with tank mix applications at either rate suggested antagonistic interactions, providing 73% (54 g ai ha^{-1}) and 65% (76 g ai ha^{-1}) less than expected control (89%-95%). At 28 DAA, observed control (97%-99%) of clethodim 54 and 76 g ai ha^{-1} plus dicamba in dual tank application was similar to clethodim applied at 76 g ai ha^{-1} (94%). However, mixing clethodim with dicamba regardless of application rates of clethodim resulted in antagonistic interactions with 66%-70% lower than expected control (91%-94%). Duenk et al. (2023) found antagonistic interactions with clethodim 30 g ai ha^{-1} + dicamba 600 g ae ha^{-1} for controlling glufosinate/glyphosate-resistant volunteer corn 28 DAA, observing 54% control, 26% less than expected. In addition, Perkins et al. (2021) found that the addition of a drift reduction agent (DRA) at 0.25% v/v further induced antagonism between clethodim (105 g ai ha^{-1}) + dicamba (560 g ae ha^{-1}) for junglerice [*Echinochloa colona* (L.) Link] control 21 DAA (66%) compared to clethodim + dicamba with no DRA (77%), and clethodim at the same rate (88%).

Typical symptoms of ACCase-inhibiting herbicides (Devkota et al., 2024) on volunteer corn plants were present in the treatments containing clethodim (Figure 3). Mixing clethodim with dicamba in the same tank reduced volunteer corn control from 7-28 DAA. Merritt et al. (2021) found that mixing clethodim at 68 g ai ha^{-1} + dicamba 562 g ae ha^{-1} provided 17% control of broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], 18% control of giant foxtail (*Setaria faberi* Herrm.), and 35% control of barnyardgrass [*Echinocloa crus-galli* (L.) P. Beauv.] 7 DAA, which was 30%, 25%, and 22% lower than clethodim applied alone at the same rate. This reaffirms that antagonism between these two herbicides can reduce the efficacy of clethodim for control of grass weed species besides volunteer corn. The results of this study suggest that dual tank technology could alleviate antagonism, especially 14-28 DAA. The literature has reaffirmed this notion of using a dual tank between clethodim and dicamba. Merritt et al. (2020) observed 92% control of volunteer corn with clethodim (68 g ai ha^{-1}) + dicamba (281 g ae ha^{-1}) 4 WAA (92%) using a dual tank system compared to mixing the two chemicals in line (60%), or tank mixing the chemicals at the same rate (88%). Furthermore, in Merritt et al. (2020) study, when the dicamba rate was increased from 281 g ae ha^{-1} to 562 g ae ha^{-1}, using a separate boom provided 7-14% higher control than tank-mix applications and 15-35% higher control than mix-in-line applications for control of Italian rygrass (*Lolium perenne* L.) and broadleaf signalgrass. The applications of dicamba at a half than labeled rate in dicamba-resistant soybean were not antagonistic in this scenario; however, dicamba application at this rate is not recommended.

The selection and use of adjuvants in clethodim applications and their respective effect on efficacy has been noted (Zollinger & Howatt, 2006). Soltani et al. (2023) observed that when applying clethodim at 45 g ai ha^{-1}, the use of adjuvants, specifically phosphate ester surfactant, high surfactant oil concentrate (HSOC), and HSOC + methlyated seed oil (MSO), increases glyphosate-resistant volunteer corn control by 75-79% 4 weeks after application compared to no adjuvant use. In respect to using a dual tank application technique with clethodim and dicamba, further research may be needed to confirm adjuvant use.

Volunteer corn density

Clethodim applied at 54 or 76 g ai ha^{-1} recorded 0.3 plants m^{-2} 14 DAA (Table 3). Mixing clethodim at 54 g ai ha^{-1} with dicamba in the same tank resulted in 3.7 volunteer corn plants m^{-2} compared with 2.6 volunteer corn plants m^{-2} with 76 g ai ha^{-1} + dicamba. In contrast, clethodim and dicamba applied from the dual tank system recorded ≤ 0.5 volunteer corn plants m^{-2}. At 28 DAA, dual tank applications of clethodim 54 (0.3 plants m^{-2}) and 76 g ai ha^{-1} (0 plants m^{-2}) with dicamba provided similar volunteer corn densities compared to clethodim applied alone at 76 g ai ha^{-1}, which recorded 0.6 plants m^{-2}, respectively. Duenk et al. (2023) observed 6 volunteer corn plants m^{-2} in clethodim at 30 g ai ha^{-1} + dicamba 600 g ae ha^{-1} tank-mix application 42 DAA compared to 4 plants m^{-2} when clethodim applied alone. Furthermore, Underwood et al. (2016) observed 6 volunteer corn plants m^{-2} in tank-mix applications of clethodim 37.5 g ai ha^{-1} + dicamba 600 g ae ha^{-1} 42 DAA, suggesting antagonistic interactions with 3 plants higher than the expected value of 3 plants m^{-2}. Furthermore, in this study, when the rate of clethodim was increased from 37.5 g ai ha^{-1} to 45 g ai ha^{-1}, volunteer corn density decreased to 3 plants m^{-2}. These notions continue to support the idea that dicamba mixed with clethodim mitigates effective reduction of volunteer corn density. With this, the increase of clethodim rate may reduce this effect, thus further improving volunteer corn control and density reduction.

Soybean injury and yield

Soybean injury was marginal in this study with 5% soybean injury observed at 7-14 DAA when dicamba was applied alone (Table 4). Mixing dicamba and clethodim in the same tank or dual tank applications did not result in any soybean injury. Soybean yield varied between herbicide treatments (P-value = 0.01; Figure 4). Dual tank application of clethodim 54 g ai ha^{-1} (4,195 kg ha^{-1}) and 76 g ai ha^{-1} (4,448 kg ha^{-1}) with dicamba provided 1,128 kg ha^{-1} and 1,235 kg ha^{-1} higher yield than mixing them in the same tank, respectively. Mixing clethodim at 54 g ai ha^{-1} with dicamba in the same tank resulted in soybean yield of 3,067 kg ha^{-1}, a 26% reduction compared to dual tank applications at similar rates. Dicamba applied alone provided the lowest soybean yield of 2,459 kg ha^{-1} as it is broadleaf weed herbicide with no activity on volunteer corn (Table 2). Hence, competition from volunteer corn density as high as 6 plants m^{-2} (28 DAA) reduced soybean yield by 45% compared to the highest soybean yield (4,448 kg ha^{-1}) with clethodim 76 g ai ha^{-1} + dicamba 558 g ae ha^{-1} applied in dual tank (separate tank). Alms et al. (2016) found that volunteer corn at 4.4 plants m^{-2} can reduce soybean yield by 51%, suggesting it as more competitive than other weed species commonly found in soybean fields in the Midwest.

PRACTICAL IMPLICATIONS

Clethodim alone at either rate (54 or 76 g ai ha^{-1}) provided 90%-95% control of glufosinate/glyphosate-resistant volunteer corn 21-28 DAA (Table 2). If weed pressure of other species is a non-factor, this would still be a viable option. However, in cases where dicamba is selected as the foliar broadleaf herbicide in dicamba-resistant soybean, the addition of clethodim to control glufosinate/glyphosate-resistant volunteer corn can result in reduced efficacy. In this study, clethodim (54 or 76 g ai ha^{-1}) mixed with dicamba 558 g ae ha^{-1} in the same tank provided 21%-28% control of volunteer corn, suggesting antagonistic interaction as observed control was 66%-70% less than expected control 28 DAA. As a direct result of antagonism, growers may consider applying dicamba and clethodim in two separate applications.

The results from this study suggest that clethodim (54 or 76 g ai ha^{-1}) and dicamba 558 g ae ha^{-1} applied from separate tanks using dual tank technology can overcome clethodim antagonism from dicamba in a single pass. When clethodim and dicamba were applied using dual tank, it provided similar control (≥ 94%) of glyphosate/glufosinate-resistant volunteer corn as clethodim (≥ 90%) 14-28 DAA. If mixed with dicamba, it is suggested using clethodim 54 g ai ha^{-1} for volunteer corn < 30 cm tall, and 76 g ai ha^{-1} for 30-60 cm tall volunteer corn (Lingenfelter, 2023). Harre et al. (2020) found that increasing clethodim rates in mixtures with dicamba in various adjuvant scenarios can overpower antagonistic interaction. However, if dual tank of precision sprayer is accessible, the separation of herbicides through application technique can provide excellent volunteer corn control. For example, Zimmer et al. (2023) found that using a dual tank sprayer increased volunteer corn control by 49% when separating clethodim 51 g ai ha^{-1} + *S*-metolachlor (1,390 g ai ha^{-1}) from dicamba 560 g ae ha^{-1} + glyphosate 1,260 g ae ha^{-1} compared to mixing them in a single tank. With this, many cases of herbicide antagonism have been reported pertaining to multiple cropping systems outside of soybean, such as in corn (*Zea mays L.*) and cotton (G*ossypium arboreum L.*) (Selleck & Baird, 1981; Meyer et al. 2021; Merritt et al., 2020; Zollinger and Howatt, 2006), of which monocot plants have a higher chance of antagonism compared to dicot plants (Zhang et al. 1995). If the antagonism is suspected to be a tank compatibility issue, the option of using a dual tank application technique can reduce antagonism between selected herbicides. Additional research is needed to test if dual tank technology would be beneficial in other known cases of antagonism such as quizalofop-p-ethyl + 2,4-D choline, which is commonly applied to control HR volunteer corn and glyphosate-resistant broadleaf weeds in Enlist soybean and corn. In this study, herbicides were applied broadcast without activating See and Spray technology. This feature, which comes with the sprayer, could be an added benefit in reducing herbicide use or only activating one herbicide at a time. These findings of potentially overcoming clethodim antagonism from dicamba with dual tank coupled with the potential for the use of target spray features can benefit growers by providing effective volunteer corn control in a single application while reducing herbicide use.

ACKNOWLEDGEMENTS

The authors graciously acknowledge Sean Heyen, Quentin Cooksley, Alex Chmielewski, Perry Ridgway, Kyle Afrank for their help in this project.

FUNDING INFORMATION

This study received partial funding from AKRS (John Deere). The funder was not involved in study design, collection, analysis, or interpretation of data.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

Literature Cited

Alms, J., Moechnig, M., Vos, D., & Clay, S. A. (2016). Yield Loss and Management of Volunteer Corn in Soybean. *Weed Technology*, *30*(1), 254–262. https://doi.org/10.1614/WT-D-15-00096.1

Anonymous (2020). Select Max® II Herbicide label. San Ramon, CA. https://www.greenbook.net/valent-usa-llc-agricultural-products/select-max-herbicide-with-inside- technology

Anonymous (2019). XtendiMax® Herbicide label. Creve Couer, MO. https://www.greenbook.net/bayer-cropscience/xtendimax-with-vaporgrip

Barroso, A. A. M., Albrecht, A. J. P., & Reis, F. C. (2014). Accase and glyphosate different formulations herbicides association interactions on sourgrass control. *Planta Daninha*, *32*, 619-627. https://doi.org/10.1590/S0100-83582014000300018

Beckie, H. J., Harker, K. N., Hall, L. M., Warwick, S. I., Légère, A., Sikkema, P. H., & Simard, M. J. 2006). A decade of herbicide-resistant crops in Canada. *Canadian Journal of Plant Science*, *86*(4), 1243-1264. https://doi.org/10.4141/P05-193

Butts, T., Ikley, J., Lancaster, S., Legleiter, T., Werle, R. (2023). ACCase herbicide injury in corn. Crop Protection Network, https://cropprotectionnetwork.org/encyclopedia/accase-hg-1-herbicide-injury-in-corn doi://18374jdf83f3

Ceccon, C. C., Caverzan, A., Margis, R., Salvadori, J. R., & Grando, M. F. (2020). Gene stacking as a strategy to confer characteristics of agronomic importance in plants by genetic engineering. *Ciência Rural*, *50*(6). https://doi.org/10.1590/0103-8478cr20190207

Chahal, Parminder S., and Amit J. Jhala. (2015). Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean. *Weed Technology*, *29,* no. 3, 2015, pp. 431–43, https://doi.org/10.1614/WT-D-15-00001.1.

Clay, S. A. (2021). Near-term challenges for global agriculture: Herbicide-resistant weeds. *Agronomy Journal*, *113*(6), 4463–4472. https://doi.org/10.1002/agj2.20749

Colby, S.R. (1967). Calculating synergistic and antagonistic responses of herbicide combinations. *Weeds*. 1967;15(1):20-22. doi:10.2307/4041058

Deere and Company (2023). https://www.deere.com/en/sprayers/see-spray-ultimate/

Devkota, P., Berger, S., Ferrell, J., Dittmar, P. (2024). Diagnosing herbicide injury in corn. IFAS Extension, University of Florida. https://edis.ifas.ufl.edu/publication/AG374

Dill, G. M., CaJacob, C. A., & Padgette, S. R. (2008). Glyphosate-resistant crops: adoption, use and future considerations. *Pest Management Science*, *64*(4), 326–331. https://doi.org/10.1002/ps.1501

Duenk, E., Soltani, N., Miller, R., Hooker, D., Robinson, D., Sikkema, P. (2023) Synergistic and antagonistic herbicide interactions for control of volunteer corn in glyphosate/glufosinate/2,4-d-resistant soybean. *Journal of Agricultural Science (Toronto), Vol.15,* no.4. https://doi.org/10.5539/jas.v15n4p27

ERSI GIS mapping Software (2024), version 10.8.2. Redlands, CA. https://www.esri.com/en-us/arcgis/about-arcgis/overview

Green, J.M., Siehl, D.L. (2021). History and outlook for glyphosate-resistant crops. In: Knaak, J.B. (eds) *Reviews of Environmental Contamination and Toxicology, vol 255.* Springer, Cham. https://doi.org/10.1007/398_2020_54

Harre, N. T., Young, J. M., & Young, B. G. (2020). Influence of 2,4-D, dicamba, and glyphosate on clethodim efficacy of volunteer glyphosate-resistant corn. *Weed Technology, 34*(3), 394–401. https://doi.org/10.1017/wet.2019.124

Jhala AJ, Beckie HJ, Peters T, Culpepper S, Norsworthy J (2021) Interference and management of herbicide-resistant crop volunteers. Weed Science 69:257-273

Lingenfelter, Dwight. (2023) Midseason weed control: Issues in soybeans and small grains. Penn State University Extension. https://extension.psu.edu/midseason-weed-control-issues-in-soybean-and-small-grains

Merritt, L. H., Brown-Johnson, A. E., Meredith, A. N., & Ferguson, J. C. (2021). Comparison of efficacy and detection of clethodim and glyphosate applied with dicamba and 2,4-d through tank mixture and sequential applications. *Journal of Agricultural and Food Chemistry*, *69*(1), 101-111. https://doi.org/10.1021/acs.jafc.0c05541

Merritt, L.H.; Ferguson, J.C.; Brown-Johnson, A.E.; Reynolds, D.B.; Tseng, T.-M.; Lowe, J.W. (2020). Reduced herbicide antagonism of grass weed control through spray application technique. *Agronomy* 2020, *10*, 1131. https://doi.org/10.3390/agronomy10081131

Meyer, Chris J., Norsworthy, J., Kruger, G. (2020). Antagonism in mixtures of glufosinate + glyphosate and glufosinate + clethodim on grasses. *Weed Technology*, *35 (1)*, 2021, pp. 12–21, https://doi.org/10.1017/wet.2020.49.

NK Seeds, Hopkins, MN. https://www.syngenta-us.com/soybeans/nk

Perkins, C. M., Mueller, T. C., & Steckel, L. E. (2021). Junglerice (*Echinochloa colona*) control with sequential applications of glyphosate and clethodim to dicamba. *Weed Technology*, *35*(4), 651–655. doi:10.1017/wet.2021.31

Reddy, K.N., & Nandula, V.K., (2012). Herbicide resistant crops: History, development, and current technologies *Indian Journal of Technology, 57*(1), 1-7. https://www.indianjournals.com/ijor.aspx?target=ijor:ija&volume=57&issue=1&article=001

Roma-Burgos, N., Heap, I. M., Rouse, C. E., & Lawton-Rauh, A. L. (2018). Evolution of herbicide-resistant weeds. In *Weed Control* (pp. 92-132). CRC Press. https://doi.org/10.1201/9781315155913

Rosenberg, Mark, & Deneke, Darrell. (2020) SDSU Research shows effect of volunteer corn in corn and soybeans. https://extension.sdstate.edu/sdsu-research-shows-effects-volunteer-corn-corn-and-soybeans

Selleck G.W., Baird D.D. (1981). Antagonism with glyphosate and residual herbicide combinations. *Weed Science*. 1981;29(2):185-190. doi:10.1017/S0043174500061774

Sexton, P. (2019). A look at crop rotation and soybean production. SDSU Extension, iGrow Soybean, Chapter 4. https://extension.sdstate.edu/sites/default/files/2020-03/S-0004-04-Soybean.pdf

Singh, M., Kumar, V., Knezevic, S. Z., Irmak, S., Lindquist, J. L., Pitla, S., & Jhala, A. J. (2023). Interaction of quizalofop-p-ethyl with 2,4-D choline and/or glufosinate for control of volunteer corn in corn resistant to aryloxyphenoxypropionates. *Weed Technology*, *37*(5), 471–481. doi:10.1017/wet.2023.79

Soltani, N., Shropshire, C., & Sikkema, P. H. (2023). *Control of Volunteer Glyphosate-Resistant Corn in Soybean With Clethodim Plus Adjuvants*. (n.d.). https://doi.org/10.5539/jas.v15n12p26

Soltani, N., Shropshire, C., & Sikkema, P. H. (2015). Control of volunteer corn with the AAD-1 aryloxyalkanoatete dioxygenase-1) transgene in soybean. *Weed Technology*, *29*(3), 374–379. https://doi.org/10.1614/WT-D-14-00155.1

Striegel, A. M., & Jhala, A. J. (2020). Control of volunteer corn in enlist corn and economics of herbicide programs in conventional and multiple herbicide-resistant soybean systems across Nebraska. University of Nebraska-Lincoln, Lincoln, Nebraska. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1200&context=agronhortdiss

Takano, H. K., Ovejero, R. F. L., Belchior, G. G., Maymone, G. P. L., & Dayan, F. E. (2020). ACCase-inhibiting herbicides: mechanism of action, resistance evolution and stewardship. *Scientia Agricola*, *78*(1), https://doi.org/10.1590/1678-992X-2019-0102

TeeJet Technologies, (2023). Glendale Heights, IL https://www.teejet.com/spray-applications/spray-tips/tti

TeeJet Technologies, (2023). Glendale Heights, IL. https://www.teejet.com/spray-applications/spray-tips/aixr

Underwood, M. G., Soltani, N., Hooker, D. C., Robinson, D. E., Vink, J. P., Swanton, C. J., & Sikkema, P. H. (2016). The addition of dicamba to post applications of quizalofop-p-ethyl or clethodim antagonizes volunteer glyphosate-resistant corn control in dicamba-resistant soybean. *Weed Technology*, *30*(3), 639–647. https://doi.org/10.1614/WT-D-16-00016.1

[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service, Soybean Production- United States, 2022, 2023. https://fas.usda.gov/data/production/commodity/2222000

Zollinger, R.K., and Howatt, K.A. (2006). Influence of clethodim formulation and oil adjuvants on weed control and overcoming herbicide antagonism. *ASTM Special Technical Publication*, vol. STP 1470, no. 1470, ASTM International, 2006, pp. 72–78, https://doi.org/10.1520/STP37467S.

Zimmer, M., Young, B., Johnson, W., Avent, T., Norsworthy, J., Contreras, D., Everman, W., Houston, M., Lazaro, L., Patzoldt, W. (2023). Clethodim antagonism from dicamba on volunteer corn control in soybean was resolved by using a dual tank/boom sprayer. *Poster, Weed Science Society of America Annual Meeting, 2023, Washington, DC.* https://ag.purdue.edu/btny/purdueweedscience/wp-content/uploads/2023/02/2023-WSSA-Poster-Final-Marcelo-Zimmer.pdf

Zhang, J., Hamill, A.S., Weaver, S.E. (1995). Antagonism and synergism between herbicides: trends from previous studies. *Weed Technology*, *9(1)*, 1995, pp. 86–90, https://doi.org/10.1017/s0890037x00023009.

Table 1: Herbicide treatments, rates, trade names, and application techniques used for control of glufosinate/glyphosate-resistant volunteer corn in dicamba/glufosinate/glyphosate-resistant soybean in a field experiment conducted near Clay Center, NE in 2023.

Herbicide[a]	Rate[b]	Trade Name	Manufacturer[c]	Application Technique
	g ai/ae ha^{-1}			
Clethodim	54	Select Max	Valent USA	-
Clethodim	76	Select Max	Valent USA	-
Dicamba	558	XtendiMax	Bayer	-
Clethodim + Dicamba	54 + 558	Select Max + XtendiMax	Valent USA/Bayer	Tank Mix (single tank)
Clethodim + Dicamba	76 + 558	Select Max + XtendiMax	Valent USA/Bayer	Tank Mix (single tank)
Clethodim + Dicamba	54 + 558	Select Max + XtendiMax	Valent USA/Bayer	Dual Tank (separate tank)
Clethodim + Dicamba	76 + 558	Select Max + XtendiMax	Valent USA/Bayer	Dual Tank (separate tank)

[a]Adjuvants included: Crop oil Concentrate (COC) at 1% v/v, ammonium sulfate (AMS) at 3%v/v in clethodim alone or clethodim designated tank. VaporGrip Xtra Agent (Verified; Helena Agri, Collierville, TN) at 1,449 ml ha^{-1}, and a drift reduction agent (In-place; San Fransisco, CA) at 0.5% v/v was included in dicamba alone or dicamba designated tank.
[b]Abbreviations: ai, active ingredient; ae, acid equivalent.
[c]Manufacturer: Bayer CropScience, Creve Couer, MO.; Valent USA Corporation, San Ramon, CA.

Table 2: Control of glufosinate/glyphosate-resistant volunteer corn using tank mix and dual tank applications at 7, 21, and 28 d after application (DAA) in dicamba/glufosinate/glyphosate-resistant soybean in field experiment conducted near Clay Center, NE in 2023.

Herbicide	Rate[a]	Application Technique[a]	7 DAA[b,c]		21 DAA[b,c]		28 DAA[b,c]	
	g ai/ae ha^{-1}		Observed	Expected	Observed	Expected	Observed	Expected
			---------------------------------% Control-------------------------------					
Clethodim	54	--	79 a	-	90 b	-	90 b	-
Clethodim	76	--	84 a	-	95 a	-	94 ab	-
Dicamba	558	--	0 d	-	3 e	-	3 e	-
Clethodim + Dicamba	54 + 558	TM	28 c*	79	16 d*	89	21 d*	91
Clethodim + Dicamba	76 + 558	TM	30 c*	84	30 c*	95	28 c*	94
Clethodim + Dicamba	54 + 558	DT	49 b	79	94 ab	89	97 a	91
Clethodim + Dicamba	76 + 558	DT	84 a	84	99 a	95	99 a	94

[a]Abbreviations: ae, acid equivalent; ai, active ingredient; DT, Dual Tank; TM, Tank Mix.
[b] Asterisks (*) indicate the observed and expected values are significantly different according to the t-test ($P<0.05$), suggesting antagonistic interactions.
[c]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 3: Density of glyphosate/glufosinate-resistant corn volunteers with clethodim and dicamba mixture in single tank and dual tank applications at 14 and 28 d after application (DAA) (applied at the V5-V6 volunteer corn stage) in dicamba/glufosinate/glyphosate-resistant soybean in field experiment conducted near Clay Center, NE in 2023.

Herbicide	Rate[a]	Application Technique[a]	14 DAA[b]	28 DAA[b]
	g ai/ae ha^{-1}		————plants m^{-2}—————	

Clethodim	54	--	0.25 d	1 c
Clethodim	76	--	0.25 d	0.6 cd
Dicamba	558	--	6.4 a	6.1 a
Clethodim + Dicamba	54 + 558	TM	3.7 b	4.6 b
Clethodim + Dicamba	76 + 558	TM	2.6 c	4.2 b
Clethodim + Dicamba	54 + 558	DT	0.5 d	0.3 d
Clethodim + Dicamba	76 + 558	DT	0.25 d	0 d

[a]Abbreviations: ae, acid equivalent; ai, active ingredient; DT, Dual Tank; TM, Tank Mix.
[b]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Table 4: Soybean injury for clethodim and dicamba treatments applied from a single tank or dual tank at 7, 14, and 28 d after application (DAA) in field experiment conducted near Clay Center, NE in 2023.

Herbicide*	Rate[a]	Application Technique[a]	7 DAA[b]	14 DAA[b]	28 DAA[b]
	g ai/ae ha^{-1}			%	
Clethodim	54	--	3 a	0 a	0 a
Clethodim	76	--	3 a	0 a	0 a
Dicamba	558	--	5 a	5 a	0 a
Clethodim + Dicamba	54 + 558	TM	0 a	0 a	0 a
Clethodim + Dicamba	76 + 558	TM	0 a	0 a	0 a
Clethodim + Dicamba	54 + 558	DT	0 a	0 a	0 a
Clethodim + Dicamba	76 + 558	DT	0 a	0 a	0 a
P-value			0.4	0.7	-

[a]Abbreviations: ae, acid equivalent; ai, active ingredient; DT, Dual Tank; TM, Tank Mix.
[b]Means separated within each column with no common letter(s) are significantly different according to Tukey-Kramer's LSD test at $P \leq 0.05$.

Figure 1: John Deere's precision sprayer with a.) dual tank system; b) unfolded (37 m wide boom) before application in field experiment conducted in soybean near Clay Center, NE in 2023.

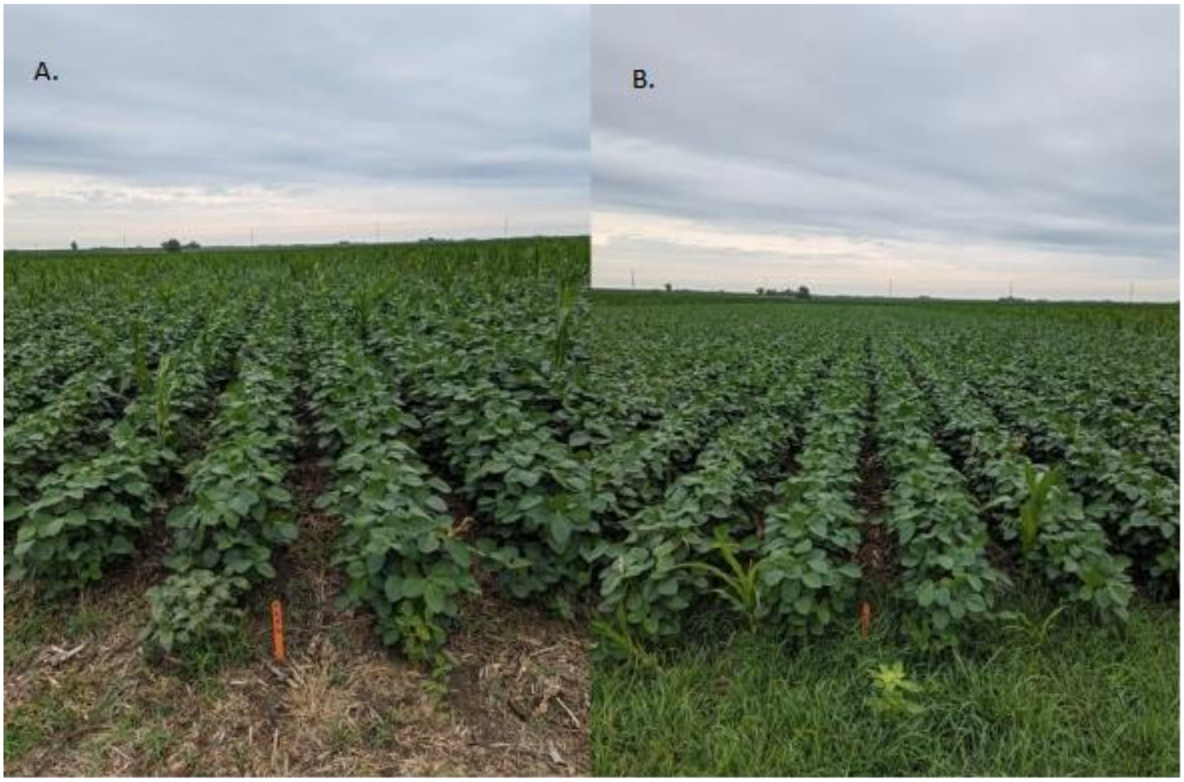

Figure 2: Volunteer corn control at 21 days after application (DAA) with clethodim + dicamba (54 + 558 g ai/ae ha^{-1}) in (a) tank mix applications and (b) dual tank applications.

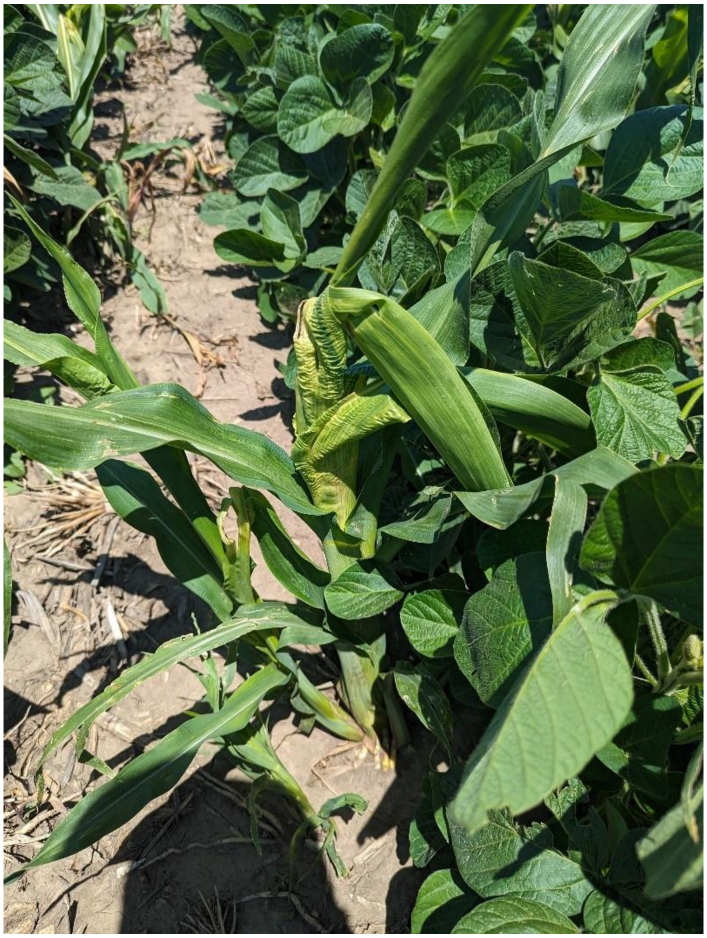

Figure 3: A partially controlled volunteer corn with a mixture of clethodim at 54 g ai ha^{-1} + dicamba 558 g ae ha^{-1} 11 days after application (DAA) in a field study conducted at South Central Ag Lab near Clay Center, NE.

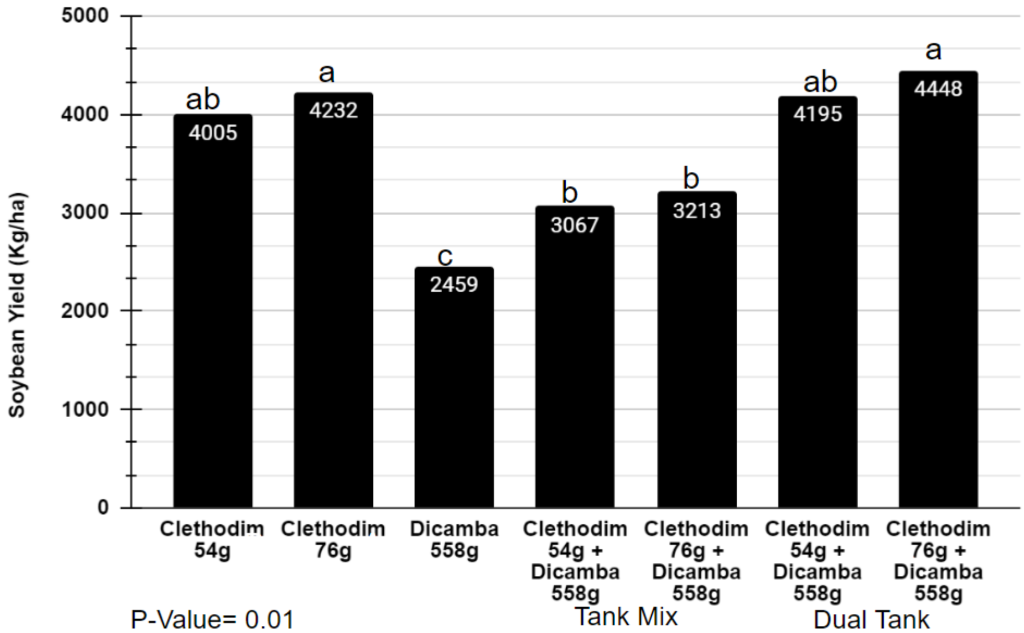

Figure 4: Soybean yield affected by application techniques (Tank-mix and Dual Tank) and herbicide treatments for control of volunteer corn in soybean in field experiment conducted near Clay Center, NE in 2023. Herbicide rates are in g ae or ai ha^{-1}.

A precision dual tank sprayer to evaluate interaction of 2,4-D choline and quizalofop-p-ethyl for control of glufosinate/glyphosate-resistant corn volunteers in corn resistant to aryloxyphenoxypropionates

Adam Leise[1], Mandeep Singh[2], Nicolas Cafaro La Menza[3], Stevan Z. Knezevic[4], Amit J. Jhala[5]

Abstract

Management of volunteer corn resistant to multiple herbicides is a challenge for corn growers in Nebraska and other states where continuous corn is a common practice. Quizalofop-p-ethyl (QPE) can provide effective control of glufosinate/glyphosate-resistant corn volunteers in corn resistant to aryloxyphenoxypropionates (Enlist corn). However, mixing QPE with broadleaf herbicides such as 2,4-D choline can have antagonistic effect for controlling volunteer corn. A new precision sprayer (John Deere's 612R) with dual tank allows for simultaneous applications of two herbicides through different nozzles, which may alleviate the physiochemical antagonism of mixing herbicides in a single tank. The objective of this study was to evaluate efficacy of QPE applied using a separate tank or mixed with 2,4-D choline in the same tank using the precision dual tank sprayer for control of glufosinate/glyphosate-resistant corn volunteers in Enlist corn. Bin-run glufosinate/glyphosate-resistant corn was planted at 54,000 seeds ha^{-1} to mimic as volunteer corn on the same day of Enlist corn planting using a circular spreader. Volunteer corn control with QPE at 39 g ai ha^{-1} + 2,4-D choline at 1,064 g ae ha^{-1} in a dual tank system (applied through a separate tank) was 60% compared to 35% control when mixing them in a single tank at 7 d after application (DAA). Mixing QPE at 39 g ai ha^{-1} + 2,4-choline at 1,064 g ae ha^{-1} improved control of volunteer corn to 70% but was 20% lower compared to applied through dual tank system 14 DAA, indicating importance of dual tank precision sprayer. QPE at both rates (39 and 77 g ai ha^{-1}) had antagonistic interaction with 2,4-D choline when mixed in the same tank at 7 and 14 DAA. At 28 DAA, the antagonistic effect was observed with QPE 39 g ai ha^{-1} in tank mix, observing 8% lower control than expected. Volunteer corn control was ≥ 92% at 28 DAA across treatments leading to similar Enlist corn yield without crop injury.

Introduction

Corn production in the United States increased to 398 million MT in 2023, an increase of 51 million MT from 2022 (USDA, 2024). In the Midwest, continuous corn remains a popular choice for farmers. In this rotation, corn kernels or ears fell during the previous year due to harvesting inefficiency or adverse weather may overwinter and emerge as volunteer corn the following spring (Newcomer, 1971; Chahal, 2014). Volunteer corn can increase pest and disease pressure in continuous corn rotations, such as potentially developing resistance to Bt traits (Marquardt et al., 2013), and can be viewed as intraspecific competitor (Marquardt et al., 2012) as twin species compete for the same resources. As hybrid corn has been diligently optimized for maximum production (Staggenbrog et al., 1999; Assefa et al., 2016), volunteer corn’s impact on hybrid corn population density could result in less-than-optimal production. Early-season volunteer corn competition can reduce hybrid corn leaf area per plant which can be directly linked to a reduction in grain yield (Marquardt et al., 2012).

Since the introduction of herbicide-resistant (HR) corn in 1996, it has been rapidly adopted with 91% of corn planted in the United States with HR traits in 2023 (USDA, 2023). Some common choices for HR hybrid corn include glufosinate and glyphosate-resistant traits. While glufosinate/glyphosate considered good options for weed control, volunteer corn emerging the following year may present a management challenge (Jhala et al., 2021). Enlist corn is resistant to 2,4-D choline and the FOP family (aryloxyphenoxypropionates) of herbicides (Anonymous, 2021) along with stacked resistance to glyphosate and glufosinate (Godar et al., 2023). The metabolism-based aryloxyalkanoate dioxygenase (AAD-1) trait in Enlist corn provides resistance to two herbicide chemical classes, which include the aryloxyphenoxypropionate (FOP) class of ACCase-inhibiting herbicides and the phenoxycarboxylic class of synthetic auxins (Godar et al., 2023; Wright et al., 2010). This trait allows growers to use quizalofop-p-ethyl (QPE) in Enlist corn to control glufosinate/glyphosate-resistant volunteer corn as selective POST herbicide option. Currently, QPE (Assure II, AMVAC Corporation, Newport Beach, CA, USA) is the only herbicide labeled to control volunteer corn in Enlist corn.

Reports of antagonism between ACC-ase inhibiting herbicides (e.g., QPE) mixed with the POST herbicide such as 2,4-D-choline have been reported (Singh et al., 2023; Duenk et al., 2023). This antagonism reduces the efficacy of QPE for controlling volunteer corn (Underwood et al., 2016; Singh et al., 2023). Weed height and more specifically tall grasses can affect herbicide efficacy and potentially antagonism, thus leading to a choice for farmers to make two separate applications (Craigmyle et al., 2013; Meyer et al., 2014). Increasing the rate of QPE can reduce antagonistic effect and increase QPE efficacy (Singh et al., 2023). However, farmers may be reluctant to increase the rate of QPE to deter this effect due to additional input costs. In addition, it is time consuming and expensive to apply grass and broadleaf weeds killing herbicides in separate application. Therefore, growers are looking for solutions to apply herbicides at the same time for broad-spectrum weed control without antagonistic effect.

John Deere (Deere and Company, Moline, IL, USA) has developed a new precision sprayer (Figure 1) equipped with a dual tank system (Figure 2) that allows for simultaneous herbicide applications from separate tanks and nozzles (John Deere, 2023). The See and Spray Ultimate™ package (equipped with Tank A and B) (Figure 2) is available on the 410R, 412R, 612R, and 616R models as of January 2024. This system allows for the herbicides to be entirely separated until they reach the plant. This system can be combined with the activation of See and Spray™ features. By utilizing the dual tank system, it can reduce or overcome herbicide interaction that otherwise occurs when mixed in the same tank. Scientific literature is lacking whether utilizing dual tank system can reduce the antagonistic effect of QPE + 2,4-D choline by maintaining QPE's efficacy for controlling volunteer corn. The objective of this study was to evaluate efficacy of QPE applied in a separate tank (dual tank) using the precision dual tank sprayer or mixed with 2,4-D choline in the same tank (tank-mix) and apply for control of glufosinate/glyphosate-resistant corn volunteers in Enlist corn. We hypothesized utilizing the dual tank system could decrease the antagonistic effect of 2,4-D choline on QPE, thus increasing QPE efficacy in controlling glufosinate/glyphosate-resistant corn volunteers. If successful, this can lead to farmers utilizing a lower rate of QPE rather than increasing rates to overcome/reduce antagonism. Furthermore, precision sprayers with dual tank systems could be tested in other crops/situations to evaluate herbicide interactions in various combinations.

Materials and Methods

Experimental Site

The field experiment was conducted in 2023 at the University of Nebraska-Lincoln's South-Central Agricultural Laboratory near Clay Center, NE. The project consisted of 2 replications, with 4 pseudo-replicates in each. Plot size was 18 m wide by 46 m long. Large plot sizes were preferred due to ease of application and sprayer coordination as the sprayer width was 120 feet with the capacity to apply herbicide on minimum of 60 feet. Enlist corn was planted at 81,000 seeds ha^{-1} on May 11. Before planting Enlist corn, glufosinate/glyphosate-resistant bin-run corn seeds were planted at 54,000 seeds ha^{-1} using a circular spreader on May 11. A preemergence (PRE) application of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron; Syngenta Crop Protection, Greensboro, NC) at 2,890 g ai ha^{-1} and glufosinate (Liberty; BASF Agriculture, Research Triangle Park, NC, USA) at 593 g ai ha^{-1} was applied on May 16. Neither Enlist corn nor volunteer corn had emerged at the time of PRE herbicide application. No fall herbicide was applied that could provide residual activity and hinder corn growth. Both replications were under a no-till program. Due to field space constraints, both replications of treatments 1-4 were under pivot irrigation, while both replications of treatments 5-7 were under rainfed conditions.

Herbicide Program

QPE (Assure II, AMVAC Corporation, Newport Beach, CA, USA) rates of 39 and 77 g ai ha^{-1} were chosen and referred to as 'lower rate' and a 'higher rate', respectively for controlling volunteer corn (Anonymous 2018a). Striegel et al., (2020) found that QPE rates of 31 and 39 g ai ha^{-1} can control glyphosate/glufosinate-resistant volunteer corn >95% at 28 d after application (DAA). Thus, selected rates were ideal for controlling volunteer corn. Treatments containing QPE included crop oil concentrate (COC) at 1% v/v. Herbicide treatments consisted of QPE at 39 and 77 g ai ha^{-1} applied alone, mixed with 2,4-D choline at 1,064 g ae ha^{-1} (Anonymous 2018b) and applied in a separate tank using the dual tank system (Table 1). In total, seven treatments were applied separately on June 15, with volunteer corn at the

V3-V4 growth stage. AIXR 11015 flat fan nozzles (TeeJet Technologies; Spraying Systems) were used for herbicide applications with a spray rate of 187 L ha^{-1} (Table 1).

Machine Design

The John Deere (Deere and Company, Moline, IL) 612R sprayer equipped with a dual tank system was used for this project (Figure 1 and Figure 2). The machine was equipped with a boom length of 36 m (120 feet). Since the plot width was 18 m, the boom was folded in half during the application. Nozzle spacing is designed at 38 cm which includes a nozzle directly over the row crop. The See and Spray™ feature was equipped on this machine but was not activated during application because herbicides were applied in broadcast application with the objective to evaluate herbicide interaction. The dual tank system, which is equipped with tanks A & B, keeps the herbicides separate from 'tip to tank', to promote the separation of active ingredients during application. Tank A is a 2,839 L capacity tank, which is larger than tank B's 1,703 L capacity. Tank A is preferred to be used for a blanket broadcast application of residual herbicides while Tank B can be used for See and Spray™ postemergence herbicide application. The machine is labeled for applications up to 19 km h^{-1} in 2023, with expected speeds of 24 km h^{-1} in 2024. Boom height was 30 cm above the crop canopy. Boom height is preferred to be between 26 cm and 48 cm above the ground or crop canopy for this machine.

Data Collection

Visual estimates of volunteer corn control were determined at 7, 14, 21, and 28 DAA on a scale of 0% to 100% where 0% indicates volunteer corn with no injury and 100% indicates complete control. Volunteer corn density was determined by counting plants in two one m^2 quadrat side by side, in a random and representative area of the plot at 14 and 28 DAA. Enlist corn injury was assessed at 14 and 28 DAA to determine any phytotoxicity damage- with 0% indicating no damage from herbicide and 100% indicating complete plant death due to herbicide injury. Enlist corn was harvested using a John Deere 9570 combine and categorized using ArcGIS PRO version 3.2 (Ersi GIS Mapping Systems, Redlands, CA).

Data Analysis

Colby (1967) developed a mathematical equation to calculate the expected control from two or more herbicides applied in a mixture.

$$E = (X + Y) - (XY)100$$

where X is the percent control of herbicide A, Y is the percent control of herbicide B, and E is the expected control with a mixture of A and B herbicides. Antagonism occurs when the mixture of herbicides leads to less control than the herbicides applied individually (Colby, 1967). The expected means of treatments containing QPE and 2,4-D choline were calculated and compared against the observed control using a *t*-test (Singh et al., 2023). Data were analyzed in SAS studio (9.4) using the PROC GLIMMIX package. Herbicide treatments and application techniques were used as fixed effects, while block was treated as a random effect. Type III fixed effect tests were used to assess fixed effects and treatment means were separated using LSMEANS with Tukey's test at $\alpha = 0.05$.

Results & Discussion

Volunteer Corn Control

QPE at 39 and 77 g ai ha^{-1} provided 73% and 83% control of volunteer corn 7 DAA, respectively (Table 2). Observed control of volunteer corn with QPE applied at 39 and 77 g ai ha^{-1} with 2,4-D choline at 1,064 g ae ha^{-1} in dual tank applications were 60% and 59%, respectively, compared with 35% and 43% control when mixed in the same tank. Colby's analysis indicated antagonism for both tank mix treatments, and dual tank applications of QPE at 77 g ai ha^{-1} at 7 DAA. QPE at 39 and 77 g ai ha^{-1} mixed with 2,4-D choline (1,064 g ae ha^{-1}) had 40% and 42% less than expected volunteer corn control, respectively. Similarly, in dual tank, the higher rate of QPE (77 g ai ha^{-1}) provided 59% volunteer corn control, 26% less than expected. Underwood et al. (2016) observed 57% control of glyphosate-resistant volunteer corn with QPE applied at 36 g ai ha^{-1} 7 DAA, which increased to 92% at 14 DAA. This suggests that QPE is a slow acting herbicide as it takes about 14 days to observe complete symptoms on sensitive grass weeds. QPE at 39 and 77 g ai ha^{-1} with 2,4-D choline provided 85% and 98% control 14 DAA when applied in a dual tank, which was 15% and 8% higher than mixing QPE and 2,4-D choline in a single tank, respectively. The observed control of QPE at 77 g ai ha^{-1} + 2,4-D choline in the dual tank provided similar control (98%) compared to QPE applied alone at the same rate, indicating importance of dual tank system because applying 2,4-D choline at the same time can provide control of glyphosate-resistant broadleaf weeds such as Palmer amaranth and waterhemp. Tank mix applications at either rate were antagonistic with observed control being 26% and 8% below the expected control for lower and higher rate of QPE, respectively. Volunteer corn control in treatments containing QPE improved to ≥ 92% 28 DAA; however, mixing QPE at 39 g ai ha^{-1} with 2,4-D choline in the same tank had an antagonistic interaction ($P=0.012$) with 7% less than expected control of 99%. QPE at 39 g ai ha^{-1} with 2,4-D choline applied using a dual tank provided 93% control of volunteer corn without antagonism, but numerically it was 6% less than expected control of 99%, and 6% lower than QPE applied alone (Table 2).

Antagonistic effect of 2,4-D choline on QPE efficacy for controlling volunteer corn seemed to minimize as the weeks progressed. Results of this study correlate with Singh et al., (2023) where 48% and 57% control 14 DAA was observed with QPE at 46 g ai ha^{-1} + 2,4-D choline 800 g ae ha^{-1}, and QPE at 93 g ai ha^{-1} + 2,4-D choline at 1,060 g ae ha^{-1} applied at V3 growth stage of volunteer corn, which improved to 91% and 98% control 28 DAA, respectively. Volunteer corn control of 99% at 28 DAA with QPE applied alone in this study reaffirms previous findings that it is an effective option for controlling glufosinate/glyphosate-resistant volunteer corn (Underwood et al., 2016). The dual tank option of a precision sprayer reduced the antagonistic effect but did not completely overcome it, especially at 7 DAA;

however, other findings suggest that QPE usually do not reach to full potential within 7 days (Underwood et al., 2016; Chahal and Jhala, 2014).

Volunteer Corn Density

QPE applied alone at either rate resulted in density of one volunteer corn plant m^{-2} 7 DAA, which was similar to QPE + 2,4-D choline applied in a dual tank (Table 3). In contrast, QPE at 39 or 77 g ai ha^{-1} mixed with 2,4-D choline in the same tank resulted in 4 volunteer corn plant m^{-2} 7 DAA. Volunteer corn density was as low as 0 to 2 plants m^{-2} in treatments that included QPE 14 and 28 DAA usually without difference among them (Table 3).

Enlist Corn Injury

QPE + 2,4-D choline did not lead to any crop injury in this study (Table 4). There was a 5-7% injury observed 7 and 14 DAA when 2,4-D choline was applied alone. These injury symptoms included green snap and brace roots. Brace root symptoms are well documented when 2,4-D is applied alone or mixed with other herbicides (Sikkema, 2017). Injury may be accentuated due to 2,4-D choline entering in the whorl of corn. Corn injury was ≤ 4% due to 2,4-D choline 28 DAA (Table 4).

Corn Yield

Corn yield was found to be statistically similar in all treatments (Figure 3). The numerically highest corn yield of 15,866 kg ha^{-1} was found in QPE at 39 g ai ha^{-1} and 15,385 kg ha^{-1} in QPE at 77 g ai ha^{-1}. With all treatments providing ≥92% control of volunteer corn 28 DAA, intraspecific competition was minimal after this point. Broadleaf weeds were controlled in this study to avoid their effect on grass weeds and corn yield. Identification of corn yield production from surviving volunteer corn was not collected nor assessed; as yield from volunteer corn may not hinder hybrid corn yield as previously mentioned.

Conclusion & Future Direction

As of 2024, QPE is the only labeled herbicide to control glufosinate/glyphosate-resistant volunteer corn in Enlist corn (Anonymous 2018a). It is suggested to increase the rate of QPE when applying with broadleaf herbicides such as 2,4-D choline due to potential antagonism (Webster 2019). With limited options, growers can increase the rate of QPE or make two separate applications to avoid antagonism. The results of this study suggest that dual tank technology can reduce antagonism of QPE mixed with 2,4-D choline even if applied at the same time, but from different tank. Mixing QPE at 39 g ai ha^{-1} with 2,4-D choline at 1,064 g ae ha^{-1} was antagonistic until 28 DAA and until 14 DAA for higher rate of QPE i.e., 77 g ai ha^{-1}. However, dual tank applications of QPE regardless of application rate (39 or 77 g ai ha^{-1}) with 2,4-D choline was additive at 14 DAA. Therefore, results suggest that dual tank technology can alleviate 2,4-D choline antagonism and improve control of glufosinate/glyphosate-resistant volunteer corn with QPE between 7 DAA-28 DAA. This is important to reduce volunteer corn competition with hybrid corn planted. Zimmer et al. (2024) found that QPE at 62 g ai ha^{-1} + 2,4-D choline at 1,065 g ae ha^{-1} applied in a dual tank provided 33% better control than mixing them in a single tank in field studies conducted in Indiana. Singh et al. (2023) further found that increasing the rates of graminicides and QPE may not be effective if the rate of broadleaf herbicides is increased.

The increase in volunteer corn control between 7 to 21 DAA with dual tank can alleviate antagonism of QPE from 2,4-D choline; however, treatments containing QPE + 2,4-D choline provided ≥ 92% control of volunteer corn 28 DAA. Provided this and similar yields across all treatments, it may not be enough ‘kickback’ to justify investment in this technology in this scenario. However, many cases of herbicide antagonism have been reported pertaining to multiple scenarios (Merritt et al., 2020; Zollinger and Howatt, 2006), to which this technology could provide alleviation if antagonism between selected herbicides is a tank compatibility issue. More research is needed to further test if dual tank technology can alleviate other known cases of antagonism among other herbicide combinations such as dicamba + clethodim or sethoxydim which are applied commonly in dicamba-resistant soybean. In this study, herbicides were applied broadcast without activating See and Spray technology. This is because both the weed and crop were corn. If volunteer corn control is in soybean, use of See & Spray technology of this precision sprayer can reduce the amount of herbicides applied compared with broadcast application; thus beneficial for growers. With improved control in higher rate applications of QPE, it may be suggested to use the higher labeled rate of QPE when mixing 2,4-D choline in the same tank. Research of adjuvants, nozzle selection, and droplet size may play an important role in pinpointing cases of antagonism (Gizotti de Moraes and Kruger, 2018; Penner 1989).

ACKNOWLEDGEMENTS

The authors graciously acknowledge Sean Heyen, Quentin Cooksley, Alex Chmielewski, Perry Ridgway, Kyle Afrank for their help in this project.

This chapter has been submitted to the Agroecosystems, Geosciences, and Environment Journal for publication.

FUNDING INFORMATION

This study received a partial funding from AKRS (John Deere). The funder was not involved in study design, collection, analysis, or interpretation of data.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

Literature Cited

Assefa, Y., Vara Prasad, P.V., Carter, P., Hinds, M., Bhalla, G., Schon, R., Jeschke, M., Paszkiewicz, S.and Ciampitti, I.A. (2016). Yield responses to planting density for US modern corn hybrids: A synthesis-analysis. *Crop Science, 56: 2802-2817*.

Anonymous (2015). Acuron® Herbicide Label. Syngenta Crop Protection, Greensboro, NC. https://www.greenbook.net/syngenta-llc/acuron

Anonymous (2018a). Assure® II Herbicide label. Newport Beach, CA. https://www.greenbook.net/amvac/assure-ii-herbicide

Anonymous (2019). Liberty® Herbicide label. Research Triangle Park, NC: BASF. https://www.cdms.net/ldat/ldG9N002.pdf

Anonymous (2018b). Enlist One® Herbicide Label. Corteva Agriscience, Indianapolis, IN https://www.greenbook.net/corteva-agriscience/enlist-one

Craigmyle, B. D., Ellis, J. M., & Bradley, K. W. (2013). Influence of Weed Height and Glufosinate plus 2,4-D Combinations on Weed Control in Soybean with Resistance to 2,4-D. *Weed Technology*, *27*(2), 271–280. http://www.jstor.org/stable/43702047

Chahal, P., & Jhala, A. J. (2014). Control of herbicide-resistant volunteer corn in herbicide-resistant soybean. University of Nebraska-Lincoln, Lincoln, Nebraska.

Chahal, P. S., & Jhala, A. J. (2015). Herbicide Programs for Control of Glyphosate-Resistant Volunteer Corn in Glufosinate-Resistant Soybean. *Weed Technology*, *29*(3), 431–443. doi:10.1614/WT-D-15-00001.1

Colby SR. (1967). Calculating synergistic and antagonistic responses of herbicide combinations. *Weeds*.1967;15(1):20-22. doi:10.2307/4041058

Deen, W., Allan Hamill, Christy Shropshire, Nader Soltani, & Peter H. Sikkema. (2006). Control of Volunteer Glyphosate-Resistant Corn (Zea mays) in Glyphosate-Resistant Soybean (Glycine max). *Weed Technology*, *20*(1), 261–266. http://www.jstor.org/stable/4495672

Deere and Company. (2023). Moline, IL. https://www.deere.com/en/sprayers/see-spray-ultimate.

Duenk, E.L. (2022). Optimization of weed control in E3 soybean [*Glycine max* (L.) Merr.]. [master's thesis, Guelph, ON: The University of Guelph. 162 p] Google Scholar

a

Godar AS, Norsworthy JK, Barber TL. (2023). Enlist™ corn tolerance to preemergence and postemergence applications of synthetic auxin and ACCase-inhibiting herbicides. *Weed Technology*. 2023;37(2):147-155. doi:10.1017/wet.2023.25

Jhala AJ, Beckie HJ, Peters T, Culpepper S, Norsworthy J (2021) Interference and management of herbicide-resistant crop volunteers. Weed Science 69:257-273

Merritt, L.H.; Ferguson, J.C.; Brown-Johnson, A.E.; Reynolds, D.B.; Tseng, T.-M.; Lowe, J.W. (2020). Reduced Herbicide Antagonism of Grass Weed Control through Spray Application Technique. *Agronomy* 2020, *10*, 1131. https://doi.org/10.3390/agronomy10081131

Marquardt P.T., Terry R.M., Johnson W.G. (2013). The impact of volunteer corn on crop yields and insect resistance management strategies. *Agronomy*. 2013; 3(2):488-496.

Marquardt, P. T., Terry, R., Krupke, C. H., & Johnson, W. G. (2012). Competitive effects of volunteer corn on hybrid corn growth and yield. *Weed Science*, *60*(4), 537–541. http://www.jstor.org/stable/23363040

Meyer, C. J., and Norsworthy, J.K. (2019). Influence of Weed Size on Herbicide Interactions for Enlist^{TM} and Roundup Ready® Xtend® Technologies. *Weed Technology*, vol. 33, no. 4, 2019, pp. 569–77. *JSTOR*, https://www.jstor.org/stable/26753358. Accessed 28 Apr. 2024.

Newcomer, JL. (1971). Volunteer Corn. *Crops and Soils Magazine*, vol. 24, no. 1, 1971, pp. 10-14

Penner, D. (1989). The Impact of Adjuvants on Herbicide Antagonism. *Weed Technology*, vol. 3, no. 2, 1989, pp. 227–31, https://doi.org/10.1017/S0890037X00031729.

Porter, P.M., Lauer, J.G., Lueschen, W.E., Ford, J.H., Hoverstad, T.R., Oplinger, E.S. and Crookston, R.K. (1997). Environment affects the corn and soybean rotation effect. Agron. J., 89: 442-448. https://doi.org/10.2134/agronj1997.00021962008900030012x

Ruen, D. C., Scherder, E. F., Ditmarsen, S. C., Prasifka, P. L., Ellis, J. M., Simpson, D. M., Gallup, C. A., & Hopkins, B. W. (2017). Tolerance of Corn with Glyphosate Resistance and the AAryloxyalkanoate Dioxygenase Trait (AAD-1) to 2,4-D Choline and Glyphosate. *Weed Technology*, *31*(2), 217–224. https://www.jstor.org/stable/26567394

Sikkema, P. (2017). "Situational with Sikkema" Field Crop News, University of Guelph.
Singh, M., Kumar, V., Knezevic, S. Z., Irmak, S., Lindquist, J. L., Pitla, S., & Jhala, A. J. (2023). Interaction of quizalofop-p-ethyl with 2,4-D choline and/or glufosinate for control of volunteer corn in corn resistant to aryloxyphenoxypropionates. *Weed Technology*, *37*(5), 471–481. doi:10.1017/wet.2023.79

Staggenborg, S.A., Fjell, D.L., Devlin, D.L., Gordon, W.B., Maddux, L.D. and Marsh, B.H. (1999). Selecting optimum planting dates and plant populations for dryland corn in Kansas. Journal of Production Agriculture, 12: 85-90. https://doi-org.libproxy.unl.edu/10.2134/jpa1999.0085

Striegel, A.M., and Amit J.J. (2020). Control of volunteer corn in enlist corn and economics of herbicide programs in conventional and multiple herbicide-resistant soybean systems across Nebraska. University of Nebraska-Lincoln, 2020.

Striegel A, Eskridge K.M., Lawrence N.C., et al. (2020). Economics of herbicide programs for weed control in conventional, glufosinate-, and dicamba/glyphosate-resistant soybean across Nebraska. *Agronomy Journal*. 2020; 112: 5158–5179. https://doi-org.libproxy.unl.edu/10.1002/agj2.20427

Duenk, E., Soltani, N., Miller, R.,Hooker, D., Robinson, D., Sikkema, P. (2023). Synergistic and antagonistic herbicide interactions for control of volunteer corn in glyphosate/glufosinate/2,4-D-resistant soybean." *Journal of Agricultural Science (Toronto),* https://doi.org/10.5539/jas.v15n4p27.

TeeJet Technologies, (2023). Glendale Heights, IL. https://www.teejet.com/spray-applications/spray-tips/aixr

[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service, Corn Production- United States, 2022, 2023.

Underwood, M. G., Soltani, N., Hooker, D. C., Robinson, D. E., Vink, J. P., Swanton, C. J., & Sikkema, P. H. (2016). The Addition of Dicamba to POST Applications of Quizalofop-p-ethyl or Clethodim Antagonizes Volunteer Glyphosate-Resistant Corn Control in Dicamba-Resistant Soybean. *Weed Technology*, *30*(3), 639–647. https://doi.org/10.1614/WT-D-16-00016.1

Webster, L. C., Strategies to Overcome Antagonism of Quizalofop-p-ethyl when Applied in Mixture with Other Herbicides. (2019). LSU Master's Theses. 4898. https://repository.lsu.edu/gradschool_theses/4898

Wright, T.R., Shan, G., Walsh, T.A., Lira, J.M., Cui, C., Song, P., Zhuang, M., Arnold, N.L. Lin, G., Yau, K., Russell, S.M., Cicchillo, R.M., Peterson, M.A., Simpson, D.M., Zhou, N., Ponsamuel, J., Zhang, Z. (2010). Robust crop resistance to broadleaf and grass herbicides provided by aryloxyalkanoate dioxygenase transgenes. Proc Natl Acad Sci USA 107:20240–20245.

Zollinger, R.K. (2020). Grass antagonism with dicamba + clethodim. North Dakota State University. https://www.ag.ndsu.edu/cpr/weeds/grass-antagonism-with-dicamba-clethodim-07-06-17

Zollinger, R.K, and Howatt, K.A. (2006). Influence of Clethodim Formulation and Oil Adjuvants on Weed Control and Overcoming Herbicide Antagonism. *ASTM Special Technical Publication*, vol. STP 1470, no. 1470, ASTM International, 2006, pp. 72–78, https://doi.org/10.1520/STP37467S.

Zimmer, M., Contreras, D., Everman, W., Lammers, C., Spotanski, J., Lazaro, L., Johnson, W., Young, B. (2024). Clethodim and Quizalofop Antagonism from 2,4-D on Volunteer Corn Was Not Resolved by Using a Dual-Tank Spray System. Weed Science Society of America- Southern Weed Science Society Joint Meeting, 2024.

Table 1: Herbicide treatments, rates, products, and application technique used for control of glufosinate/glyphosate resistant volunteer corn in Enlist™ corn in field experiments conducted at Clay Center, NE in 2023.

Herbicide*	Rate	Trade Name	Application Method
	g ai/ae ha^{-1}		

Quizalofop-p-ethyl	39	Assure II	-
Quizalofop-p-ethyl	77	Assure II	-
2,4-D Choline	1,064	Enlist One	-
QPE + 2,4-D Choline	39 + 1,064	Assure II + Enlist One	Tank Mix (single tank)
QPE + 2,4-D Choline	77 + 1,064	Assure II + Enlist One	Tank Mix (single tank)
QPE + 2,4-D Choline	39 + 1,064	Assure II + Enlist One	Dual Tank (separate tank)
QPE + 2,4-D Choline	77 + 1,064	Assure II + Enlist One	Dual Tank (separate tank)

*Quizalofop-p-ethyl was mixed with Crop Oil Concentrate (COC) at 1% v/v

Table 2: Control of glufosinate/glyphosate-resistant corn volunteers with quizalofop-p-ethyl (QPE) and 2,4-D choline in a single tank and dual tank at 7, 21, and 28 d after application (DAA) when applied at the V4 volunteer corn growth stage in Enlist™ corn in field study conducted at Clay Center, NE in 2023.

Herbicide***	Rate	A.T.**	7 DAA		14 DAA		28 DAA	
	g ai ha^{-1}		Observed	Expected	Observed	Expected	Observed	Expected
			%					
QPE	39		73 ab	--	93 ab	--	99 a	
QPE	77		83 a	--	98 a	--	99 a	
2,4-D Choline	1,064		11 e	--	15 e	--	13 c	
QPE + 2,4-D Choline	39+1,064	Tank-mixed	35 d	75*	70 d	96*	92 b	99*

QPE + 2,4-D Choline	77+1,064	Tank-mixed	43 cd	85*	90 bc	98*	97 a	99
QPE + 2,4-D Choline	39+1,064	Dual tank	60 b	75	85 c	96	93 ab	99
QPE + 2,4-D Choline	77+1,064	Dual tank	59 bc	85*	98 a	98	99 a	99

[A] Asterisks (*) indicate the observed and expected values are significantly different according to the t-test (P<0.05), suggesting antagonistic interactions.
[B]**A.T.= Application Technique
[C]*** QPE= Quizalofop-p-ethyl

Table 3: Density of glufosinate/glyphosate-resistant corn volunteers with quizalofop-p-ethyl (QPE) and 2,4-D choline mixture in single tank and dual tank applications at 7, 21, and 28 d after application (DAA) applied at the V4 volunteer corn stage in Enlist Corn™ at in field study conducted at Clay Center, NE in 2023.

Herbicide*	Rate	A.T.*	7 DAA	14 DAA	28 DAA
	g ai ha^{-1}				
			Plants m^{-2}		
QPE	39	--	1 c	0 c	0 b
QPE	77	--	1 c	0 c	0 b
2,4-D Choline	1,064	--	5 a	5 a	4 a
QPE + 2,4-D Choline	39+1,064	Tank-Mixed	4 ab	2 b	1 b
QPE + 2,4-D Choline	77+1,064	Tank-Mixed	4 b	1 c	0 b
QPE + 2,4-D Choline	39+1,064	Dual Tank	1 c	0 c	0 b
QPE + 2,4-D Choline	77+1,064	Dual Tank	1 c	0 c	0 b

[A] *A.T.= Application Technique

B ** QPE= Quizalofop-p-ethyl

Table 4: Enlist™ corn crop injury for quizalofop-p-ethyl (QPE) and 2,4-D choline treatments when applying from a single tank or dual tank in field experiments conducted near Clay Center, NE in 2023.

Herbicide*	Rate	A.T.*	7 DAA	14 DAA	28 DAA
	g ai ha^{-1}				
			%		
QPE	39	--	0 a	0 a	0 a
QPE	77	--	0 a	0 a	0 a
2,4-D Choline	1,064	--	7 a	5 a	0 a
QPE + 2,4-D Choline	39+1,064	Tank-Mix	0 a	0 a	0 a
QPE + 2,4-D Choline	77+1,064	Tank-Mix	0 a	0 a	0 a
QPE + 2,4-D Choline	39+1,064	Dual Tank	0 a	0 a	0 a
QPE + 2,4-D Choline	77+1,064	Dual Tank	0 a	0 a	0 a

[A] *A.T.= Application Technique
[B] **QPE= Quizalofop-p-ethyl

Figure 1: John Deere's precision sprayer with 120 feet long boom unfolded before application of herbicides in a study conducted at the University of Nebraska–Lincoln's South Central Ag Lab near Clay Center, Nebraska.

Figure 2: John Deere's precision sprayer with dual tank system with capacity to apply two herbicides in a separate tank in a study conducted at the University of Nebraska–Lincoln's South Central Ag Lab near Clay Center, Nebraska.

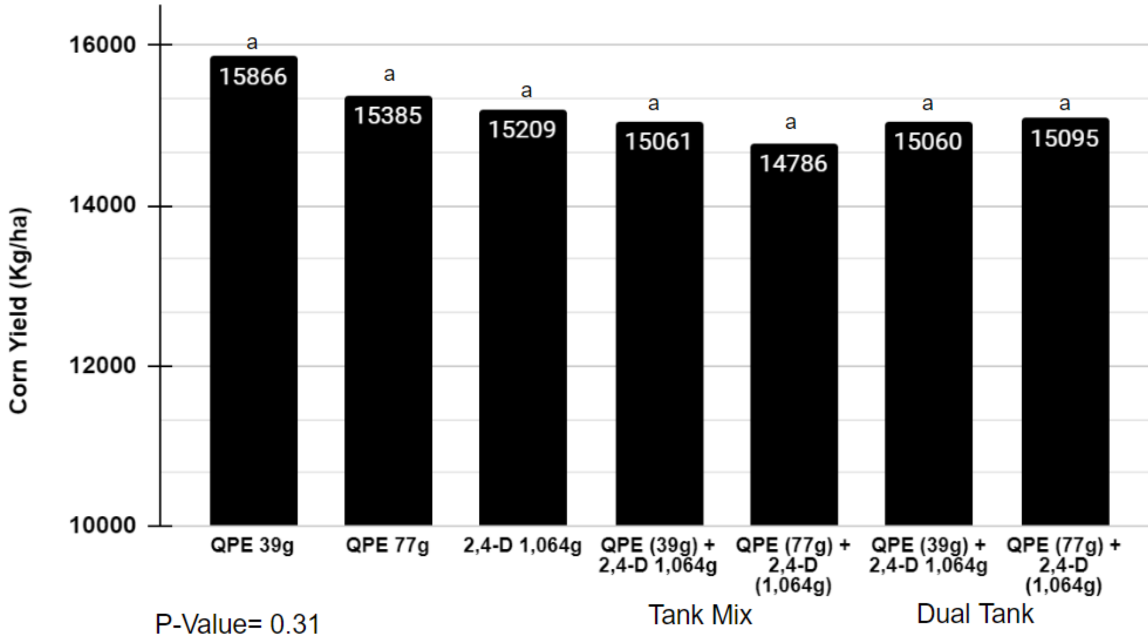

Figure 3: Effect of herbicide programs and application technique for control of glufosinate/glyphosate-resistant corn volunteers on yield of Enlist corn in a field study conducted near Clay Center, NE in 2023.