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Evaluation of row width and nozzle selection on spray coverage and weed control in flooded rice

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Abstract

Barnyardgrass and other troublesome weeds have become a major problem for producers in a flooded rice system. Cultural control options and more efficient herbicide applications have become a priority to increase efficiency and weed control in rice. This study aimed to determine the effects of row width and nozzle selection on spray coverage and weed control in a flooded rice system. A field experiment was conducted at 7 site-years (Lonoke, AR, in 2021 and 2022; Pine Tree, AR, in 2021 and 2022; Rohwer, AR, in 2022; and Stoneville, MS, in 2021 and 2022) as a randomized complete block split-plot design. Five nozzles (XR, AIXR, TTI, TTI60, and AITTJ60) (subplot factor) were used for herbicide applications, and plots were drill-seeded in four row widths (whole plot factor) (13, 19, 25, and 38 cm). A droplet size experiment was conducted to evaluate the droplet size and velocity of each nozzle type used in the field experiment. Overall, as row width increased, barnyardgrass density increased. The rice grown in a wider width took longer to generate canopy closure, allowing weed escapes in the crop. For example, the 13-cm width had a 12 percentage point canopy coverage increase compared to the 38-cm row width at the preflood timing resulting in a reduction of six barnyardgrass plants per square meter. The smallest droplet size-producing nozzle (XR) provided greater weed control throughout the study but is more prone to drift. The dual-fan nozzles (AITTJ60 and TTI60) had variable weed control impacts, and it was difficult to predict when this might occur; however, they did have increased deposits on water-sensitive cards compared to single-fan counterparts (AIXR and TTI). In conclusion, a narrower row width (e.g., 19-cm or less) and a smaller droplet size producing nozzle (XR) are optimal for barnyardgrass control in a flooded rice system.

Introduction

Rice is considered a staple food crop for nearly half of the world's population. Increasing urban environments have led to a reduction of land availability, highlighting the importance of high-yielding environments and being more efficient in rice production (Prasad et al. 2017). In the latest growing season of 2022–2023, the state of Arkansas was the lead rice producing state in the United States with over 50% of rice production in the country (USDA-NASS 2023). Weeds are among the major biotic stresses in rice causing upwards of 70 to 80% yield reduction in direct-seeded rice (Dass et al. 2017; Smith 1968). One of the main weed control options in the United States is the use of chemical herbicides. With the continuous use of these herbicides, survey respondents in Arkansas reported using three or more herbicide applications per field to combat the weed pressure and seventy-eight percent of the respondents had high concerns about herbicide-resistant weeds (Butts et al. 2022). An earlier survey found similar results regarding herbicide-resistant weed concerns in rice (Norsworthy et al. 2007). This emphasizes the importance of developing more efficient integrated weed management strategies to produce a more sustainable rice production system in the future (Mahajan et al. 2014).

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Row width manipulation is effective in other crops for efficient weed control. Research conducted in soybean [*Glycine max* (L.) Merr.] provided evidence that the crop yield increased and weed yield decreased as the row width decreased (Butts et al. 2016; Hock et al. 2006; Wax and Pendleton 1968). Profitability also increased when switching to narrow row (38 cm) soybean from wider row widths (76 cm) (Lambert and Lowenberg-DeBoer 2003). This provides support that similar results may be achievable in a rice production system with new higher tillering capabilities of hybrid rice enhancing canopy closure (Chauhan and Opeña 2013; N.H. Reed unpublished data). A similar crop to rice is soft red winter wheat (*Triticum aestivum* L.) and a study in eastern Kansas investigated row widths of 19 and 38 cm. In this study, weed emergence increased and yield decreased for the 38-cm width compared to the 19-cm width (Shoup and Adee 2014). One major pest to control in rice is barnyardgrass, and narrow widths of 20 cm or less have the potential to reduce weed density leading to less seed in the soil seedbank (Butts et al. 2022; Chauhan and Johnson 2010; Schwartz-Lazaro and Copes 2019). The recommended row width in Arkansas is between 10 and 25 cm depending on crop production limitations of farmers, such as equipment and field conditions (Hardke 2022). These results could impact weed control in a rice production system.

In any crop production system, profitability from yield is an important consideration for farmers. In some situations, a rice crop with no weed control implementation can cause yield reductions of 94% to 96% (Chauhan and Johnson 2011). In a drill-seeded rice system, increased grain yield and reduced weed infestations were observed as a result of rice planted in a narrow row width of 19 to 25 cm, which in return, can reduce herbicide use by up to 50% in some conditions (Dass et al. 2017; Jones and Snyder 1987; Lytle et al. 2021).

Herbicide optimization is critical to maximize weed management efforts, and a site-specific management approach would be beneficial throughout the mid-south (Butts et al. 2018). Some regulations limit the use of certain application methods, like particular nozzles, because of the drift potential due to smaller droplet sizes. The greater the droplet size, the more drift potential is reduced; however, herbicide efficacy has been reduced with increased droplet sizes (Butts et al. 2019; Carter et al. 2017; Creech et al. 2015). To achieve an effective herbicide application, all parameters such as nozzle selection, droplet size, and spray drift potential should be considered by producers (Chethan et al. 2019).

The most effective pesticide applications are made when the greatest area of the plant is covered with spray solution. Dual-fan nozzles increased spray coverage and efficacy compared to a single-fan highlighting the potential of providing greater weed control while using a larger droplet size to reduce drift potential at the same time (Ferguson et al. 2016). Smaller droplet size-producing nozzles provide greater spray coverage than larger droplet size-producing nozzles, which could increase weed control with an effective herbicide application (Priess et al. 2021). Velocity is another component that can impact coverage and drift potential; when the vertical velocity is increased, and the horizontal velocity is decreased, then a reduction of drift is observed (Farooq et al. 2001). Smaller droplet size and lower terminal velocity increased the effectiveness and coverage of solution on plants compared to larger droplets and a higher velocity (Lake 1977). As a result, the objective of this research was to determine the effects of row width manipulation and nozzle selection on coverage and weed control in a flooded rice system across diverse environments and herbicide application systems.

Materials and Methods

Field Sites

Field experiments were conducted across 7 site-years in 2021 and 2022. The first location occurred at the University of Arkansas Pine Bluff Small Farm Outreach Center near Lonoke, Arkansas (34.85° N, 91.88°W) with the soil being an Immanuel silt loam (fine-silty, thermic Oxyaquic Glossaqualfs) consisting of 14% sand, 72% silt, 14% clay, and 1.25% organic matter with a pH of 5.6. The planting dates at this location were June 16, 2021, and May 16, 2022. The second location occurred at the University of Arkansas System Division of Agriculture Pine Tree Research Station near Colt, Arkansas (35.13°N, 90.96°W) with a Calhoun silt loam (fine-silty, thermic Typic Glossaqualfs) consisting of 12% sand, 70% silt, 18% clay, and 1.02% organic matter with a pH of 5.6. The rice was drill-seeded on July 7, 2021, and June 7, 2022, at this location. The third location of the experiment was at the University of Arkansas System Division of Agriculture Rohwer Research Station near Watson, Arkansas (33.79°N, 91.29°W) and was only conducted in 2022. The soil was a Sharkey clay (very-fine, thermic Chromic Epiaquerts) consisting of 2% sand, 45% silt, 53% clay, and 1.98% organic matter with a pH of 6.8. The planting date at this location was June 28, 2022. The last location was at the Delta Research and Extension Center near Stoneville, Mississippi (33.40°N, 90.86°W). The soil classification of this site was a Sharkey clay (very-fine, thermic Chromic Epiaquerts) consisting of 2% sand, 32% silt, 66% clay, and 2.4% organic matter with a pH of 7.5. The Stoneville location was planted on May 26, 2021, and May 11, 2022.

Experimental Design

This experiment was designed as a split-plot randomized complete block (24 treatments) replicated four times with four nontreated controls, one for each row width. The whole-plot factor consisted of four row widths of 13, 19, 25, and 38 cm. These row width treatments were selected because 1) 19- and 25-cm row widths are currently commercially available, 2) a reduced width of 13 cm was hypothesized to aid in cultural weed management, and 3) a 38-cm row width may become commercially available in the future with enhancements in precision planting technology. This wider row width may aid in facilitating crop rotation capabilities with reduced equipment inputs. The subplot factor consisted of five nozzle types used for herbicide applications, including three single-fan and two dual-fan nozzles. Single-fan nozzles comprised the XR-11002 (Extended range), AIXR-11002 (Air induction extended range), and TTI-11002 (Turbo TeeJet induction). Dual-fan nozzles comprised the TTI60-11002 (Turbo TeeJet induction dual fan) and AITTJ60-11002 (Air induction turbo TeeJet). All nozzles were from TeeJet Technologies (Spraying Systems, Inc., Glendale Heights, IL). These nozzles were selected based on commercial usage, the range of droplet sizes produced, and the comparable designs of the dual-fan and single-fan nozzles.

At all site-years, a hybrid rice cultivar, 'RT7521 FP' (RiceTec Inc., Alvin, TX), was drill-seeded at 128 seeds m^{-2}. Plot dimensions were 7.6 m long and 1.5 m wide, and standard University of Arkansas recommendations for nutrients, pests, and irrigation/flooding were used (Hardke et al. 2022).

High levels of weed infestation and previous survey results indicated commercial rice fields in Arkansas typically receive three to four herbicide applications including a preemergence and two to three postemergence applications (Butts et al. 2022). As a result, the decision was made to apply a noncommercial herbicide

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program within this research targeting grass, sedge, and broadleaf weed species specific to each respective site-year. This noncommercial program included two herbicide applications (one preemergence and one postemergence) to allow assessment of the cultural factors but provide the opportunity for trials to be harvested for yield assessment. Additionally, as it is common commercially for a singular nozzle type to be used throughout an entire growing season across multiple herbicide programs, a fixed herbicide program was not implemented so as to provide insights into nozzle selection impacts across a range of herbicide application systems. Applications were made with an all-terrain vehicle equipped with a CO_2-pressurized sprayer calibrated to deliver 94 L ha^{-1} at 8 km h^{-1} at the Arkansas locations, rotating each nozzle for individual applications. At the Mississippi location, applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 5.6 km h^{-1} with each appropriate nozzle.

Across site-years, a preemergence application of clomazone at 315 g ai ha^{-1} (Command® 3ME; FMC, Philadelphia, PA) and saflufenacil at 75 g ai ha^{-1} (Sharpen; BASF, Morrisville, NC) was applied. Different postemergence applications were made across site years depending on the certain type of weed species and density that were observed in the experiment. The postemergence applications at the Lonoke and Pine Tree locations in 2021 consisted of cyhalofop at 313 g ai ha^{-1} (Clincher® SF; Corteva Agriscience, Indianapolis, IN) and halosulfuron + thifensulfuron at 35 + 4.5 g ai ha^{-1} (Permit Plus; Gowan, Yuma, AZ). The postemergence application at the Lonoke site in 2022 was bentazon applied at 560 g ai ha^{-1} (Basagran®; BASF Canada, Mississauga, ON). The postemergence application at the Stoneville site in 2021 and 2022 was imazethapyr applied at 105 g ai ha^{-1} (Preface®; ADAMA, Raleigh, NC) and quinclorac at 420 g ai ha^{-1} (Facet®; BASF). Applications at the Pine Tree and Rohwer locations in 2022 consisted of fenoxaprop at 122 g ai ha^{-1} (Ricestar HT; Gowan), bispyribac-sodium at 3.5 g ai ha^{-1} (Regiment®; Valent U.S.A., Walnut Creek, CA), and halosulfuron + thifensulfuron at 35 + 4.5 g ai ha^{-1}. All postemergence applications contained a 1% vol/vol rate of crop oil concentrate. The appropriate nozzle for each treatment was used to apply both the preemergence and postemergence herbicide applications.

Data Collection

Barnyardgrass density was assessed from two 0.25-m^2 quadrants per plot at the 5- to 6-leaf rice stage (preflood) and the preharvest stage. All density data were then converted to a square meter for ease of presentation.

At the postemergence application for the Arkansas locations, one water-sensitive spray card (7.6 × 5.1 cm; Spraying Systems, Inc.) was placed per plot parallel to the soil surface at 15 cm above the soil at the top of the rice canopy to measure percent spray coverage and spray deposits per square centimeter. The cards were initially yellow, and as the herbicide mixture encountered the card, the solution would cause the droplets to turn blue. After the application, the cards were allowed to air dry before being handled to prevent any data contamination. Water-sensitive spray cards were analyzed using USDA-ARS DepositScan for the above factors (Zhu et al. 2011).

A small, unmanned aircraft system (sUAS) (Inspire 2; DJI Technology Co., Nanshan, Shenzhen, China) was manually flown to take digital images from directly above of each plot at the preflood and panicle differentiation rice stages to assess canopy coverage. Images from sUAS were taken at the Lonoke, Pine Tree, and Rohwer locations in 2022 only. In 2021, technological complications caused the images to not be taken accurately to assess canopy coverage. At the Stoneville, MS location, technological difficulties did not allow for proper data collection. The images were captured at a 46-m height across all plots for consistency in the analysis software. Aerial images were analyzed using FieldAnalyzer software (Green Research Services, Fayetteville, AR). Green pixel counts were measured in each plot to determine the canopy coverage percentage.

Before rice harvest, barnyardgrass panicles were clipped and averaged from two 0.25-m^{-2} quadrants per plot and placed in paper bags. Barnyardgrass inflorescences were dried at 66 C for 3 to 5 d to constant mass. The panicles were then hand threshed and cleaned to gather the barnyardgrass seed. The mass of 100 barnyardgrass seeds was recorded and divided by the total mass of cleaned seed to determine the seed production per 0.25 m^{-2} of each plot. Seed production was converted to a square meter scale for ease of presentation.

Rough rice grain yield was collected at harvest with a small-plot research combine. The entire width of the plot was harvested at the Lonoke, Rohwer, and Stoneville locations. At the Pine Tree location, two identical plot combines with different header widths were equally calibrated and used according to the row width of the plot. This was done because no single header could harvest the entirety of the plot at this location. With a fixed header size and variable row widths, it would have resulted in a variable number of rows entering the combine. Therefore, a 51-cm header was used to harvest two rows of the 25-cm row width and four rows of the 13-cm width per plot. A 72-cm header harvested two rows of the 38-cm row width and four rows of the 19-cm width per plot.

Statistical Analyses

Site-year and block nested within site-year were run as random effects across all analyses to generate broader conclusions across diverse environments as indicated in the overall objective, and with 5 site-years of data, it was deemed statistically beneficial (Midway 2022). Row width and nozzle type were considered fixed effects. All data were analyzed using ANOVA. Rice canopy coverage and water-sensitive card spray coverage were analyzed using SAS software (v. 9.5; SAS Institute, Cary, NC) with the GLIMMIX procedure and a beta distribution. Preflood barnyardgrass density, preharvest panicle counts, and seed production were analyzed in JMP Pro 17.0 (SAS) using the GLIMMIX procedure with a Poisson distribution. Rough rice yield was analyzed in JMP Pro 17.0 using the GLIMMIX procedure and a normal distribution. All means were separated using Tukey's honestly significant difference (HSD) test with an alpha value of 0.05.

Droplet Size and Velocity Experiment

A laboratory experiment was conducted at the Lonoke Extension Center near Lonoke, AR, to evaluate the droplet size and velocity from each nozzle type used in the previously described field experiment. Data collected included the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, driftable fines (defined as the percent of spray volume less than 200 µm), average droplet velocity, and maximum droplet velocity. The $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ are the droplet diameters in which 10%, 50%, and 90% of the spray volume are contained in droplets with a lesser diameter, respectively. Spray classifications were also determined according to standard S572.1 as published by the American Society of Agricultural and Biological Engineers (ANSI/ASABE 2020).

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Table 1. $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$; driftable fines; and spray classification determined by using an Oxford Laser system in a spray chamber.[a]

Nozzle	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	Driftable fines[b]	Spray classification[c]
		µm		%	
AITTJ60	221 b	441 c	757 c	9.07	VC
AIXR	130 c	304 d	634 d	25.68	C
TTI	320 a	733 a	1200 a	2.94	UC
TTI60	333 a	600 b	943 b	2.41	UC
XR	91 d	160 e	302 e	66.98	F
P-value	<0.0001	<0.0001	<0.0001		

[a] Means followed by the same letter within a column are not different based on Tukey's honestly significant difference test (α = 0.05).
[b] Driftable fines are defined as the percentage of spray volume contained in droplets with diameters less than 200 µm.
[c] Spray classifications were determined using American Society of Agricultural and Biological Engineers standard S572.1, where F indicates Fine; M, Medium; C, Coarse; VC, Very Coarse; EC, Extremely Coarse; and UC, Ultra Coarse.

Measurements were made using the VisiSize P15 Portable Particle/Droplet Image Analysis System (Oxford Lasers, Imaging Division, Oxford, UK) using similar methods to previous research (Kouame et al. 2022). The system was installed within a Generation 4 Research Track Sprayer (Devries Manufacturing, Hollandale, MN). Before measurements, the VisiSize P15 components were aligned and calibrated according to manufacturer's recommendation. The spray chamber was operated at 276 kPa and traversed at 0.22 m s^{-1} to allow for sampling of spray droplets from the entire spray plume. Data acquisition was set to measure diameter and velocity of 2,500 individual droplets per replication, with three separate replications being recorded, giving a total of 7,500 individual droplets measured per treatment.

The $DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$ average droplet velocity, and maximum droplet velocity data were subjected to ANOVA using the GLIMMIX procedure in SAS software (v. 9.5) with a gamma distribution. Treatment means were separated using Tukey's HSD (α = 0.05). The percent of driftable fines were predicted using the Rosin-Rammler equation:

$$V(d) = 100 - 100 * \exp\left(-\left(\frac{d}{c}\right)^{m}\right) \tag{1}$$

where V is the cumulative percent volume of droplets with the diameter lower than a certain value (d); c is the characteristic droplet diameter, defined as the diameter at which the cumulative volume fraction is 63.2%; and m is a constant indicating the uniformity of the distribution.

Additionally, the four-parameter log-logistic model (Eq. 2) was fit to droplet size and velocity paired measurements data to predict droplet velocities of specific droplet size spray particles from each nozzle type:

$$Y = c + \frac{d - c}{1 + \exp[b(\log(x) - \log(e)]} \tag{2}$$

where Y is the droplet exit velocity (m s^{-1}), b is the slope at the inflection point, c is the lower limit (m s^{-1}), d is the upper limit (m s^{-1}), e is the inflection point, and x is the droplet size (µm). All curve fittings were accomplished using nonlinear least squares regression with the R package (version 4.0.0) (R Core Team 2021).

Results and Discussion

Droplet Size and Velocity Data

The $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ were impacted by nozzle type (Table 1). The TTI produced the largest droplet diameter at the $D_{v0.5}$ and $D_{v0.9}$, followed by the TTI60, AITTJ60, AIXR, and XR, respectively. The TTI and TTI60 produced the largest $D_{v0.1}$, followed by the AITTJ60, AIXR, and XR, respectively. The $D_{v0.1}$ had a range from 91 µm emitted by the XR to 333-µm emitted by the TTI60. The $D_{v0.5}$ ranged from 160-µm emitted by the XR to 733-µm emitted by the TTI, which provided spray classifications ranging from Fine to Ultra Coarse. The $D_{v0.9}$ ranged from 302-µm emitted by the XR to 1200-µm emitted by the TTI. It is important to take into consideration not only the $D_{v0.5}$, often considered the average droplet size, but also the $D_{v0.1}$ and $D_{v0.9}$ as these values provide an overall observation of the complete droplet size distribution. A droplet size distribution with a similar $D_{v0.5}$, but reduced $D_{v0.1}$ and/or increased $D_{v0.9}$ would indicate a less homogenous spray droplet size mixture, which is often undesirable from an efficacy and spray drift mitigation perspective. Driftable fines were calculated to find the potential of the solution to move off target (Stainer et al. 2006). In this study, driftable fines was defined as the percentage of spray volume contained in droplets with diameters less than 200 µm. The XR and AIXR nozzles had the greatest potential to move off-target with 66.98% and 25.68% driftable fines, respectively. For high drift concerns, nozzles like the TTI and TTI60 should be considered as they produced the fewest driftable fines, but a loss of weed control has been observed due to the increased droplet size (Butts et al. 2018, 2019; Meyer et al. 2016). Creech et al. (2015) found a 176% change in droplet size from the XR to a TTI nozzle, which is similar to the results found in this study.

Both the average and maximum velocities were also impacted by nozzle type (Table 2). The XR and AIXR produced the fastest average droplet velocities, followed by the TTI60, TTI, and AITTJ60 nozzles, respectively. The predicted velocities at specific droplet sizes numerically followed this similar trend. Greater velocities have the potential to reduce weed control because the droplets will bounce or shatter more easily, but they do have the potential to reduce drift (Kouame et al. 2022). When comparing single-fan versus dual-fan nozzles, the single-fan AIXR produced a smaller $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ than its counterpart, the dual-fan AITTJ60. Conversely, the single-fan TTI had a greater $D_{v0.5}$ and $D_{v0.9}$ compared to the dual-fan TTI60. Overall, the nozzle types evaluated in this research had a wide range of droplet sizes, drift potential, and droplet velocities that could impact resulting spray coverage and weed control.

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Table 2. Average, maximum, and predicted droplet velocity for each nozzle type in the experimental laboratory study.[a]

			Predicted velocity		
Nozzle	Average velocity	Maximum velocity	150 µm	200 µm	300 µm
	m s^{-1}				
AITTJ60	1.29 d	6.00 b	0.76	1.07	1.80
AIXR	2.04 ab	10.00 a	1.6	2.11	3.86
TTI	1.82 c	6.58 b	0.93	1.22	1.98
TTI60	2.00 b	6.12 b	0.80	1.10	1.89
XR	2.23 a	10.87 a	2.24	2.94	5.35
P-value	<0.0001	<0.0001			

[a]Means followed by the same letter within a column are not different based on Tukey's honestly significant difference test (α = 0.05).

Field Experiment

Data collected varied across site-years. Spray coverage, number of spray deposits, preflood barnyardgrass density, panicle counts, and seed production were collected from the 5 site-years conducted in Arkansas. Rice canopy coverage data were collected only in 2022 from the three Arkansas locations. Rough rice yield was collected from all 7 site-years.

No interaction between row width and nozzle type occurred across all response variables (Table 3). Across site-years, row width and nozzle main effects affected barnyardgrass density and panicle counts at the preflood and preharvest stage, respectively. At the preflood stage, row widths of 13, 19, and 25 cm had a barnyardgrass density count of 14, 15, and 16 m^{-2}, respectively (Table 4). The highest barnyardgrass density was observed in the 38-cm row width with 20 plants m^{-2}. Barnyardgrass density increased by 42% in the widest row width of 38 cm compared to 13-cm. Additional control efforts would likely be needed to reach adequate control for barnyardgrass and other weed species at the widest row width of 38-cm, and a narrower width from 13- to 25 cm likely would help reduce barnyardgrass populations.

At the preflood stage, the lowest barnyardgrass densities of 15 to 17 plants m^{-2} occurred from applications with the XR, AIXR, AITTJ60, and TTI nozzles (Table 4). The TTI60 had the greatest barnyardgrass density with 21 plants m^{-2}. At this preflood timing, only a preemergent application had been made. This would indicate there may be negative consequences resulting in greater barnyardgrass density when a TTI60 nozzle that produced an Ultra Coarse spray, low droplet velocity, and had dual-fans (Tables 1 and 2) was used for a PRE application to bare soil. However, further research is needed to fully characterize this relationship. Dual-fan nozzles can lessen the angle of spray to the target and have previously improved coverage to the leaf surface compared to a single-fan nozzle (Gossen et al. 2008). While this is the case for leaf surface coverage, it could be a different result for soil surface coverage and the ability of the herbicide to be activated.

The preharvest panicle counts followed a similar trend as the preflood density counts with reduced barnyardgrass panicles observed in narrower rice row widths. At the preharvest rice stage, the lowest number of panicles occurred in the 13-cm row width with 6 panicles m^{-2} (Table 4). Barnyardgrass panicles increased to 8 panicles m^{-2} in the 19- and 25-cm row widths compared to the 13-cm row width. The greatest number of panicles was in the 38-cm row width with 13 panicles m^{-2}. There was a 116% increase in barnyardgrass panicle counts in the widest row width of 38 cm compared to 13-cm. The use of narrower row widths such as 13 cm in rice could help reduce herbicide use and reduce weed control costs like it has in other crops like corn (*Zea mays* L.) and soybean (Forcella et al. 1992).

At the preharvest rice stage, applications from the AITTJ60, AIXR, TTI, and TTI60 nozzles resulted in similar panicle counts of 8 to 10 m^{-2} (Table 4). The fewest barnyardgrass panicle counts of 6 panicles m^{-2} occurred in rice following applications with the XR nozzle. Droplet size is considered an important factor in weed control which could explain why greater panicle density occurred in the larger droplet size producing nozzles with $D_{v0.5}$ greater than 160 µm (Table 1) (Oliveira et al. 2021). Other research has also identified better weed control from applications with a smaller droplet size producing nozzle such as the XR than larger droplet sizes (Brankov et al. 2023). Although applications from the XR nozzle provided the greatest panicle density reduction, it also had the highest driftable fine percentage (Table 1). This nozzle could potentially have the highest off-target movement of herbicides and may not be the most suitable nozzle in some cases as a result. Identifying other nozzles that can provide adequate weed control and lower driftable fines coupled with altering other application parameters, such as spray volume, should be considered when making a herbicide application.

For barnyardgrass seed production, only the main effect of row width was significant (Table 3). The narrowest row width of 13 cm resulted in 2,590 fewer barnyardgrass seeds per square meter compared to the widest row width of 38 cm (Table 4). This wide row width allowed for more weed seed to be returned to the soil seedbank increasing the likelihood of herbicide resistance evolution and negatively impacting long-term weed management. The 19- and 25-cm row widths resulted in similar barnyardgrass seed production with 4,610 and 4,390 seeds m^{-2}, respectively. A narrower row width, particularly 13 cm, provided numerically lower barnyardgrass density counts and seed production, as well as statistically lower panicle counts, thereby likely reducing the number of weed seeds returned to the soil seedbank and improving long-term weed management. In a wheat study, seed production from a single plant was three times greater in a wheat row width of 30 cm compared to a 10-cm width (Mertens and Jansen 2002).

Nozzle selection did not have statistical differences in barnyardgrass seed production, but the fewest number of seeds numerically were produced following applications with the XR nozzle with 3,900 seeds m^{-2}. However as previously stated, this nozzle has the highest drift potential and should be used cautiously.

Water-sensitive spray cards were used to measure percent spray coverage and number of spray deposits across all five Arkansas 5 site-years. A significant nozzle-type main effect was observed for both response variables (Table 5). The order of nozzle type from greatest to least percent spray coverage occurring from applications with their respective use were XR = AIXR > AITTJ60 = TTI = TTI60. Increased coverage from a herbicide application can lead to greater weed control. This was observed by Carter et al. (2017) where they found 5% to 6% lower grass control from applications using TTI nozzles compared to AIXR and DriftGuard (Spraying Systems, Inc.) nozzles.

The number of spray deposits from each nozzle type trended similarly to the percent spray coverage, except 36 more spray deposits per square centimeter were observed for the AITTJ60 compared to the AIXR (Table 5). Additionally, applications from the TTI60 resulted in 51 more deposits per square centimeter than the TTI nozzle. This indicates although the dual-fan AITTJ60 and TTI60 nozzles did not have greater percent spray coverage, they

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Table 3. P-values from ANOVA for barnyardgrass density at preflood and preharvest rice stages, canopy coverage percentage for 2022, barnyardgrass seed production before harvest, and rough rice yield across site-years.[a,b]

	Barnyardgrass		Canopy coverage			
Source	Preflood density	Preharvest panicles	Preflood	Panicle differentiation	Barnyardgrass seed	Rough rice yield
	P > *F*					
Row	**<.0001**	**<.0001**	**0.0014**	**0.0007**	**0.0489**	0.4848
Nozzle	**<.0001**	**0.0011**	0.5214	0.9029	0.4721	0.9875
Row*Nozzle	0.2349	0.4074	0.8914	0.8128	0.9043	0.9988

[a] Values in bold indicate statistical significance at α = 0.05.

[b] Canopy coverage is from 2022 only due to excessive weed pressure and software limitations. Five site-years of data were collected for barnyardgrass preflood density, preharvest panicles, and seed production. Rough rice yield was collected across all 7 site-years.

Table 4. Barnyardgrass preflood density, preharvest panicle counts, and seed production across site-years.[a,b]

Main effect	Preflood barnyardgrass density	Preharvest barnyardgrass panicles	Barnyardgrass seed production
	No. m^{-2}		
Row width[c]			
13	14 b	6 c	3,220 b
19	15 b	8 b	4,610 ab
25	16 b	8 b	4,390 ab
38	20 a	13 a	5,810 a
Nozzle			
AITTJ60	17 b	8 a	4,080
AIXR	16 b	9 a	4,830
TTI	16 b	10 a	5,550
TTI60	21 a	10 a	4,170
XR	15 b	6 b	3,900

[a] Means followed by the same letter within a main effect and column are not different based on Tukey's honestly significant difference test (α = 0.05).

[b] Five site-years were used for barnyardgrass density, panicles, and seed production.

[c] Row width is measured in centimeters.

Table 5. Water-sensitive spray cards across 5 site-years in Arkansas including percent coverage and number of spray deposits for each nozzle used at the postemergence application.[a,b,c]

Nozzle	Coverage	Spray deposits
	%	No. cm^{-2}
AITTJ60	22.6 b	176 b
AIXR	29.2 a	140 c
TTI	21.3 b	77 d
TTI60	20.7 b	128 c
XR	30.7 a	27 a
P-value		
Nozzle	**<0.0001**	**<0.0001**
Row width	0.4732	0.6711
Row width*nozzle	0.8910	0.7301

[a] Means followed by the same letter within a column are not different based on Tukey's honestly significant difference test (α = 0.05).

[b] Five site-years were used for coverage percentage and spray deposits on water-sensitive spray cards.

[c] Values in bold indicate statistical significance at α = 0.05.

did have an increased number of spray deposits compared to the similar droplet size producing single-fan AIXR and TTI nozzle counterparts, respectively (Table 1). As a result, there could be more complex interactions that would occur on resulting weed control that coverage alone would not indicate, and dual-fan nozzles could be beneficial in spraying from two different angles that single-fan nozzles are not capable of. Previous research indicated that dual-fan nozzles produced greater coverage on vertical leaves, but the single-fan outperformed the dual-fan nozzles on horizontal leaves in wheat (Ozkan et al. 2012).

Nozzle selection effects on weed control were variable throughout the study. Priess et al. (2021) found that increased coverage or decreases in droplet size did not consistently impact Palmer amaranth groundcover. Another study evaluating a big dataset of various spray application factors also found that weed control results can be highly variable and that several different factors working together, such as droplet size, spray volume, herbicide active ingredient, etc., may help explain this variability with each application (Knoche 1994). The dual-fan nozzles generally did not impact weed control compared to single-fan nozzles; however, there was an interesting trend with barnyardgrass seed production in relation to water-sensitive card droplet deposition. Although not statistically different, there was numerically less barnyardgrass seed produced from applications using the AITTJ60 and TTI60 dual-fan nozzle treatments compared to the AIXR and TTI single-fan nozzle counterparts, respectively (Table 4). The barnyardgrass seed production numerical trend resulting from applications using the various nozzle types generally mirror the spray deposit results from the water-sensitive card data, indicating that the increased number of droplet deposits may have aided in weed control efforts, at least to a small extent. Further research is needed to validate these observations. Overall, the best-suited nozzle for applications to control barnyardgrass in rice would be the XR, but drift concerns and herbicide regulations could prevent this from being an option in some cases. In these instances, the AITTJ60 dual-fan nozzle may be recommended as it had increased droplet size compared to the XR, and applications using the AITTJ60 resulted in similar barnyardgrass densities, numerically less barnyardgrass seed production, and the second greatest number of spray deposits on water-sensitive cards compared to all other nozzles tested.

For rice canopy coverage at both preflood and panicle differentiation rice stages, the row width main effect was significant (Table 3). At the preflood stage, rice canopy coverage decreased as the row width increased (Table 6). A 12 percentage-point increase in canopy coverage was observed from the 13-cm width compared to the 38-cm width. This rice canopy coverage trend for row width links to the barnyardgrass data previously discussed in which the greatest barnyardgrass density, panicles, and seed production occurred in the wider row width (Table 4). This early in the rice growth stages, the widest width provided the least amount of rice canopy closure allowing for greater weed escapes (Table 4). The greatest rice canopy coverage occurred in the 13-cm row width and resulted in the numerically lowest preflood barnyardgrass density

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Table 6. Rice canopy coverage at preflood and panicle differentiation growth stages across site-years in 2022, and rough rice yield across all site-years.[a,b]

	Canopy coverage		
Main effect	Preflood	Panicle differentiation	Rough rice yield
	%	%	kg ha^{-1}
Row width[c]			
13	44 a	83 a	12,460
19	43 a	83 a	12,470
25	38 ab	79 ab	12,510
38	32 b	73 b	11,950
Nozzle			
AITTJ60	40	81	12,400
AIXR	42	79	12,250
TTI	40	78	12,330
TTI60	40	80	12,270
XR	38	79	12,480

[a] Means followed by the same letter within a main effect and column are not different based on Tukey's honestly significant difference test (α = 0.05).
[b] Three site-years were used for canopy coverage due to excessive weed pressure and software limitations and 7 site-years were used for rough rice yield.
[c] Row width is measured in centimeters.

(Tables 4 and 6). The wider row width likely allowed greater light transmittance to the soil and increased diurnal temperature fluctuations compared to narrower row widths for weeds to be able to germinate, emerge, and grow. Light is the most important suppression tactic compared to allelopathy or physical impedance for weed control (Norsworthy 2004; Teasdale 1993; Thompson and Grime 1983). Teasdale (1995) saw similar results in corn where the crop canopy in a 38-cm row width reduced light transmittance 1 wk earlier than a 76-cm row width.

The panicle differentiation rice stage is classified as the last vegetative stage and the start of the reproductive stage where vegetative production ceases and the seed head begins formation (Moldenhauer et al. 2022). At this growth stage, similar trends were observed to the preflood stage where the rice canopy coverage percentage decreased as row width increased; however, the 19- and 25-cm row widths resulted in the same canopy coverage percentage as the 13-cm row width (Table 6). The lowest canopy coverage percentage occurred in the 38-cm row width with a 10-percentage point decrease compared to the 13- and 19-cm widths. The canopy coverage of the 38-cm row width at the rice panicle differentiation growth stage provides further evidence as to why higher panicle counts and increased barnyardgrass seed production occurred in this row width. Light transmittance was able to penetrate the rice canopy more and likely increased diurnal temperature fluctuations allowing for greater weed escapes and enhanced weed growth (Norsworthy and Oliveira 2007; Thompson and Grime 1983). In soybean, 15- to 36-cm widths suppressed weeds by 92% because of a higher rate of canopy closure likely indicating similar potential in rice (Teasdale and Frank 1983).

Across all site-years, no differences were observed from the main effects of row width and nozzle selection on rough rice yield. Despite the negative consequences observed on weed management, it would indicate that wider row widths may be feasible agronomically since there were no row width impacts on yield; although additional weed management efforts would be required for long-term success. This was previously observed in soybean where row width did not affect crop yield (Butts et al. 2016). Conversely, a previous rice study planted in conventional cultivars did see an increase of rice yields in narrower rows compared to wider rows (Jones and Snyder 1987). One reason for the lack of a row width effect on rice yield in the present research may be due to the use of a hybrid cultivar which could have led to enhanced competitiveness against weeds allowing for similar rice yields across row widths (N.H. Reed, unpublished data). Greater density of barnyardgrass has been found to lower yields in a rice production system (Smith 1968). This could mean that higher weed pressure in a field could lead to a greater impact from narrower row widths and increased yields compared to a wider row width. Even in lower weed pressure environments, additional weed control strategies would need to be considered for wider row widths to reduce weed seed from returning to the soil seedbank affecting long-term weed management.

Practical Implications

Overall, trends across site-years identified that as row width increased, barnyardgrass density, panicle counts, and seed production also increased. Throughout the study, better weed control and similar rice yields were observed in the 13-cm row width. The wider row width of 38-cm maintained similar yields and resulted in minimal weed densities and seed production compared to other row widths in a low weed-pressure environment. However, it should be acknowledged that the delayed planting dates within this research and resulting barnyardgrass emergence timings may have influenced the overall results. Future research should explore the role of rice planting date and barnyardgrass emergence timings paired with these cultural management efforts to further examine their impacts. Applications using smaller droplet size-producing nozzles like the XR resulted in greater coverage but are more prone to drift potential compared to the other nozzle types tested. Overall, there could be potential for applications with dual-fan nozzles, particularly the AITTJ60, to aid in weed control in some conditions. While it was observed that an increased number of deposits on water-sensitive cards occurred from applications from the AITTJ60 and TTI60 dual-fan nozzles, there was no consistent increased barnyardgrass control in the field studies compared to single-fan counterparts. Further field research evaluating these nozzle types should be conducted to investigate efficacy with other prominent weeds in rice. In conclusion, the 13-cm row width would be a viable choice to use in rice production to aid in weed management needs, but it would require additional equipment purchased by growers. The 19-cm row width would likely still be the most feasible because it is the industry standard, and producers would not be required to purchase new equipment for similar results regarding weed control, rice canopy coverage, and rice yield. An appropriate nozzle selection for all rice growing scenarios could not be made because of variable responses; therefore, selecting a row width based on equipment availability and weed densities was deemed more important for weed control and yield potential.

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References

ANSI/ASABE (2020) Spray nozzle classification by droplet spectra. St. Joseph, MI: American Society of Agricultural and Biological Engineers

Brankov M, Simic M, Ulber L, Tolimir M, Chachalis D, Dragicevic V (2023) Effects of nozzle type and adjuvant selection on common lambsquarters (*Chenopodium album*) and johnsongrass (*Sorghum halepense*) control using nicosulfuron in corn. Weed Technol 37:156–164

Butts TR, Norsworthy JK, Kruger GR, Sandell LD, Young BG, Steckel LE, Loux MM, Bradley KW, Conley SP, Stoltenberg DE, Arriaga FJ, Davis VM (2016) Management of pigweed (*Amaranthus* spp.) in glufosinate-resistant soybean in the Midwest and Mid-South. Weed Technol 30:355–365

Butts TR, Samples C, Franca L, Dodds D, Reynolds D, Adams J, Zollinger R, Howatt K, Fritz B, Hoffmann C, Kruger G (2018) Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Manag Sci 74:2020–2029

Butts TR, Samples C, Franca L, Dodds D, Reynolds D, Adams J, Zollinger R, Howatt K, Fritz B, Hoffmann C, Luck J, Kruger G (2019) Droplet size impact on efficacy of a dicamba-plus-glyphosate mixture. Weed Technol 33:66–74

Butts TR, Kouame KBJ, Norsworthy JK, Barber LT (2022) Arkansas rice: Herbicide resistance concerns, production practices, and weed management costs. Front Agron 4:881667

Carter O, Prostko E, Davis J (2017) The influence of nozzle type on peanut weed control programs. Peanut Sci 44:93–99

Chauhan BS, Johnson DE (2010) Implications of narrow crop row spacing and delayed *Echinochloa colona* and *Echinochloa crus-galli* emergence for weed growth and crop yield loss in aerobic rice. Field Crops Res 117:177–182

Chauhan BS, Johnson D (2011) Row spacing and weed control timing affect yield of aerobic rice. Field Crops Res 121:226–231

Chauhan BS, Opeña J (2013) Implications of plant geometry and weed control options in designing a low-seeding seed-drill for dry-seeded rice systems. Field Crops Res 144:225–231

Chethan CR, Singh PK, Dubey RP, Subhash C, Dibakar G (2019) Herbicide application methodologies: Influence of nozzle selection, droplet size, and spray drift on effective spraying-a review. Innov Farming 4:45–53

Creech CF, Henry SR, Fritz BK, Kruger GR (2015) Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. Weed Technol 29:298–310

Dass A, Shekhawat K, Choudhary AK, Sepat S, Rathore SS, Mahajan G, Chauhan BS (2017) Weed management in rice using crop competition—a review. Crop Prot 95:45–52

Farooq M, Balachandar R, Wulfsohn D, Wolf TM (2001) PA—Precision agriculture: Agricultural sprays in cross-flow and drift. J Agric Eng Res 78:347–358

Ferguson J, Hewitt A, O'Donnell C (2016) Pressure, droplet size classification, and nozzle arrangement effects on coverage and droplet number density using air-inclusion dual fan nozzles for pesticide applications. Crop Prot 89:231–238

Forcella F, Westgate ME, Warnes DD (1992) Effect of row width on herbicide and cultivation requirements in row crops. Am J Alternative Agr 7:161:167

Gossen BD, Peng G, Wolf TM, McDonald MR (2008) Improving spray retention to enhance the efficacy of foliar-applied disease- and pest-management products in field and row crops. Can J Plant Pathol 58:611–622

Hardke J (2022) Rice stand establishment. Pages 29–38 *in* Arkansas Rice Production Handbook. Little Rock: University of Arkansas System Division of Agriculture Cooperative Extension Service

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci 54:38–46

Jones DB, Snyder GH (1987) Seeding rate and row spacing effects on yield and yield components of drill-seeded rice. J Agron 79:623–626

Knoche M (1994) Effect of droplet size and carrier volume on performance of foliar-applied herbicides. Crop Prot 13:163–178

Kouame KBJ, Butts TR, Werle R, Johnson WG (2022) Impact of volatility agents on dicamba and glyphosate spray solution pH, droplet dynamics, and weed control. Pest Manag Sci 79:857–869

Lake JR (1977) The effect of drop size and velocity on the performance of agricultural spray. Pestic Sci 8:515–520

Lambert DM, Lowenberg-DeBoer J (2003) Economic analysis of row spacing for corn and soybean. J Agron 95:564–573

Lytle M, Hardke J, Roberts T, Frizzell D, Castaneda-Gonzalez, Clayton T, Frizzell T, Hale K, Amos L (2021) Influence of rice row spacing and seeding rate on stand density and grain yield. Pages 262–264 *in* Arkansas Rice Research Studies 2020. Little Rock: University of Arkansas System Division of Agriculture Cooperative Extension Service

Mahajan G, Ramesha MS, Chauhan BS (2014) Response of rice genotypes to weed competition in dry direct-seeded rice in India. Sci World J 2014: e641589

Mertens SK, Jansen JH (2002) Weed seed production, crop planting pattern, and mechanical weeding in wheat. Weed Sci 6:748–756

Meyer CJ, Norsworthy JK, Kruger GR, Barber TL (2016) Effect of nozzle selection and spray volume on droplet size and efficacy of Engenia tank-mix combinations. Weed Technol 30:377–390

Midway S (2022) Random Effects. Page 174 *in* Data Analysis in R. bookdown.org. Accessed: April 5, 2024.

Moldenhauer K, Counce P, Hardke J (2022) Rice growth and development. Pages 9–20 *in* Arkansas Rice Production Handbook. Little Rock: University of Arkansas System Division of Agriculture Cooperative Extension Service

Norsworthy JK (2004) Soybean canopy formation effects on pitted morningglory (*Ipomoea lacunosa*), common cocklebur (*Xanthium strumarium*), and sicklepod (*Senna obtusifolia*) emergence. Weed Sci 52:954–960

Norsworthy JK, Burgos NR, Scott RC, Smith KL (2007) Consultant perspectives on weed management needs in Arkansas rice. Weed Technol 21:832–839

Norsworthy JK, Oliveira MJ (2007) Light and temperature requirements for common cocklebur (*Xanthium strumarium*) germination during after-ripening under field conditions. Weed Sci 55:227–234

Oliveira OG, Lopes PR, Raetano CG, Lima RC, Prado EP (2021) Influence of droplet size on spray deposition and weed control using glyphosate. Eng Agric 41:449–457

Ozkan HE, Paul P, Derksen RC, Zhu H (2012) Influence of application equipment of spray droplets in wheat canopy. Aspects Appl Biol 114: 317–324

Prasad R, Shivay YS, Kumar D (2017) Current status, challenges, and opportunities in rice production. Pages 1–32 *in* Chauhan B, Jabran K, Mahajan G, eds. Rice Production Worldwide. New York: Springer Cham

Priess GL, Norsworthy JK, Farr R, Mauromoustakos A, Butts TR, Roberts TR (2021) Impact of auxin herbicides on Palmer amaranth (*Amaranthus palmeri*) groundcover. Weed Technol 35:768–778

R Core Team (2021) R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org. Accessed: October 1, 2023.

Schwartz-Lazaro LM, Copes JT (2019) A review of the soil seedbank from a weed scientist's perspective. Agron J 9:369

Shoup DE, Adee EA (2014) Evaluation of wheat planted on 15-inch row spacing in eastern Kansas. Crop Manag 13:1–4

Smith RJ (1968) Weed competition in rice. Weed Sci 16:252–255

Stainer C, Destain M, Schiffers B, Lebeau F (2006) Droplet size spectra and drift effect of two phenmedipham formulations and four adjuvant mixtures. Crop Prot 25:1238–1243

Teasdale JR (1993) Interaction of light, soil moisture, and temperature with weed suppression by hairy vetch residue. Weed Sci 41:46–51

Teasdale JR (1995) Influence of narrow row/ high population corn (*Zea mays*) on weed control and light transmittance. Weed Technol 9:113–118

Teasdale JR, Frank JR (1983) Effect of row spacing on weed competition in snap beans (*Phaseolus vulgaris*). Weed Sci 31:81–85

Thompson K, Grime JP (1983) A comparative study of germination responses to diurnally-fluctuating temperatures. J Appl Ecol 20:141–156

[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service (2023) Quick Stats. Rice. https://quickstats.nass.usda.gov/results/1015B916-BA1E-348F-A8CE-22256E89B41D. Accessed: July 10, 2023

Wax LM, Pendleton JW (1968) Effect of row spacing on weed control in soybean. Weed Sci 16:462–465

Zhu H, Salyani M, Fox RD (2011) A portable scanning system for evaluation of spray deposit distribution. Comput Electron Agr 76:38–43

https://doi.org/10.1017/wet.2024.25 Published online by Cambridge University Press