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Arkansas Rice: Herbicide Resistance Concerns, Production Practices, and Weed Management Costs

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An online survey to better understand current weed management practices and concerns in Arkansas rice was distributed in the fall of 2020. A total of 123 respondents from across the Arkansas rice growing region returned the survey covering a total of 236,414 rice hectares, representing about 40% of the planted Arkansas rice hectares in 2020. The most problematic weeds were *Echinochloa crus-galli* (L.) P. Beauv. (ECG), *Cyperus* spp., and *Oryza sativa* L. (weedy rice), respectively, in flooded rice, and ECG, *Amaranthus palmeri* S. Wats., and *Cyperus* spp., respectively, in furrow-irrigated rice. Most respondents (78%) reported high concern with herbicide-resistant weeds, and crop rotation (>74%) was the most common strategy listed to control and mitigate the development of herbicide-resistant weeds. A chi-square test of homogeneity showed that strategies implemented to control herbicide-resistant weeds and mitigate the evolution of herbicide-resistant weeds were not dependent on occupation type (farmer, consultant, or industry rep) nor on years of involvement in rice production. Respondents failed to control ECG 44% of the time with their first postemergence herbicide. After initial herbicide failure, 53% of respondents stated two additional herbicide applications were required to control ECG escapes while another 21% of respondents stated it was never controlled. The average ECG population at 2020 harvest was between 0.1 and 1.0 plant m^{-2} according to 44% of the respondents; however, 41% of respondents indicated an ECG density of 2 to 10 plants m^{-2} at 2020 harvest. The reported annual average cost of herbicides for rice weed control was \$266.40 ha^{-1} with ECG accounting for 81% of the total cost. Average yield loss attributed to ECG was estimated to be 505–959 kg ha^{-1} (economic loss of \$134–254 ha^{-1}). However, yield loss in the most heavily infested fields was estimated to be 757–1,464 kg ha^{-1} (economic loss of \$200–387 ha^{-1}). Effective, non-chemical approaches to weed management were ranked as the least important current research or educational effort, indicating a paradigm shift in rice producers' weed control line of thought is needed with dwindling herbicide options due to herbicide resistance.

Keywords: barnyardgrass, furrow-irrigated rice, integrated weed management (IWM), survey, weed competition, yield loss

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INTRODUCTION

Rice (*Oryza sativa* L.) has a production of ~480 million metric tons of milled rice annually and feeds more than half of the world population (Muthayya et al., 2014). The United States (US) produced 10.3 million metric tons of rough rice in 2020, and this production is accomplished mainly in the four regions of the Arkansas Grand Prairie, Mississippi Delta (parts of Arkansas, Mississippi, Missouri, and Louisiana), Gulf Coast (Texas and Southwest Louisiana), and Sacramento Valley of California (USDA-ERS, 2022). With more than 56% of the US long-grain crop (USDA-ERS, 2022), Arkansas is the leading rice producer in the country (Rouse et al., 2018). Rice production accounts for more than US$1 billion yearly in Arkansas and is a main contributing factor to its economy (USDA-NASS, 2022). However, weed competition is particularly detrimental to rice production with yield reductions > 50% (Ziska et al., 2015). *Echinochloa crus-galli* (L.) P. Beauv. (ECG) can provoke more than 55% grain yield reduction (Zhang et al., 2017) while competition from *Oryza sativa* L. (weedy rice) can induce up to 72% reduction in the number of filled grains (Martin and Tanzo, 2015). Additionally, rice weed species can decrease land value (Ottis and Talbert, 2007), increase the soil seedbank (Bagavathiannan et al., 2011), and lead to price dockages because of contaminated rice seed. Rice growers in Arkansas rely heavily on herbicides for weed management (Rouse et al., 2018; Barber et al., 2022). However, chemical weed control and alternative integrated weed management strategies in rice production systems have significantly evolved throughout the years as well as rice herbicide traits and weed spectrum.

Since the 1950s, herbicides have been used in US rice production systems to selectively manage major weeds such as *Echinochloa* spp, *Oryza sativa* L., *Diplachne* spp., *Sesbania herbacea* (P. Mill) McVaugh, and *Aeschynomene virginica* (L.) B.S.P. Propanil was introduced in Arkansas in 1959 as the first highly effective and primary herbicide for weed control in rice (Rouse et al., 2018). It was continually used for 3 decades until the development of propanil-resistant ECG in 1990 (Heap, 2022). Today, ECG resistance to multiple herbicide sites-of-action has been documented (Barber et al., 2022; Heap, 2022), leading to numerous control failures across the state when chemical control strategies are solely used.

Improving weed control in complex and dynamic weed communities requires integrated approaches to weed management (Norsworthy et al., 2012). The aforementioned escalation of herbicide resistance in important rice weeds (Heap, 2022) increased the interest in more diverse weed management tactics (Owen et al., 2015). Integrated weed management (IWM), a combination of multiple weed control methods (cultural, mechanical, biological, and chemical) (Harker and O'Donovan, 2013), is meant to help growers make informed weed-management decisions and diversify strategies based on scientific knowledge (Swanton et al., 2008). As a holistic approach, IWM provides crops a competitive advantage over weeds and reduces selection for herbicide resistance. Strategies commonly used in rice include prevention (weed-free certified seeds, clean equipment, control of volunteer-weeds in ditches, fence lines and field edges) (Norsworthy et al., 2012; Riar et al., 2013a), herbicide-resistant trait technology (Clearfield®, FullPage®, Provisia®, MaxAce®), cultural practices (cultivar selection, rotation, cover crops, planting date, irrigation management), and mechanical practices (tillage). But the level of implementation of IWM strategies and the barriers to adoption of certain IWM strategies must be evaluated for defining future research opportunities (Swanton et al., 2008).

Weed management surveys are important decision-making tools that help to improve our comprehension of the levels of adoption of production practices and the short- and long-term impact of these practices on weed populations (Norsworthy et al., 2013). They are essential for identifying the most problematic weeds and shifts in the weed spectrum and for setting future research and educational priorities (Norsworthy et al., 2007). Weed management surveys have been conducted in Arkansas in the past to evaluate growers' and consultants' perception of problematic weeds and identify weed management challenges (Norsworthy et al., 2007, 2013; Burgos et al., 2021). However, herbicide resistance has increased in Arkansas since 2011 and weed management practices have changed. A holistic evaluation of the current weed management practices, problematic weeds, costs of weed control and suggested areas of scientific research that will help growers and stakeholders to improve their ongoing management strategies is needed. Therefore, the objective of this research was to assess changes in production practices, shifts in general weed management strategies and weed spectrums, herbicide resistance concerns, and current weed management costs in Arkansas rice.

MATERIALS AND METHODS

A survey was established and distributed to better understand current weed management practices and concerns in Arkansas rice. The online survey was conducted using the Qualtrics survey platform (Qualtrics, Provo, UT 84604 USA) and was distributed through multiple vectors in the fall of 2020. A link to the survey and short description were direct-emailed to 106 members of the Arkansas Agricultural Consultant's Association and 126 Arkansas County Extension Agricultural Agents. Additionally, the survey link was distributed and publicized through multiple online media sources. The survey was available online for one month, and all respondents remained anonymous. Specific survey questions can be found in **Supplementary Material S1**.

The survey included 30 questions divided into four sections detailing respondents' demographics, general rice weed management strategies and economics, herbicide resistance, and ECG. The first section comprised demographic and background information such as employment description, years involved in rice production, county location, and number of rice hectares under supervision. The second section focused on general rice weed control details such as the prevalence of and reasons for continuous rice hectares, cost of average rice herbicide programs, and the most problematic weed species. The premise of the third section was to gather information regarding respondents' perception, concern, and mitigation strategies of herbicide-resistant weeds. The fourth section involved an in-depth investigation of ECG to evaluate the prevalence and average densities of ECG in Arkansas rice hectares, perceived herbicide resistance, and effective strategies for the successful control of this problematic weed species.

Data collected from the online survey software were directly imported into a spreadsheet software (Microsoft® Excel® for Office 365, version 2002, Redmond, WA 98052) for analysis (Shaw et al., 2009). One question requested survey participants to provide the three most problematic weeds in flooded and furrow-irrigated rice and to rank them based on importance, with 1 being the most important. Weeds listed as the #1, #2, and #3 most problematic were awarded 3, 2, and 1 points, respectively, and points were summed. Greater total points indicated the respective weed species was more consistently listed as a top problematic weed species in Arkansas rice hectares. Several questions permitted respondents to provide more than one answer resulting in a total number of weed species responses greater than the number of individual respondents. In these instances, the number of observations (n) presented refer to the number of specific individual respondents to the respective question.

Another question requested survey participants to provide two areas of weed management research that would benefit their operation's profitability and/or overall weed control. These results were summarized in two separate ways. First, each response was analyzed for singular keywords or short phrases to provide a broad spectrum look at respondent's perceived needs. These keywords were then analyzed for word frequency and a word cloud was generated using the "tm", "SnowballC", and "wordcloud" packages in R 3.5.1 statistical software (R Core Team, 2018). Secondly, responses to this open-ended question were grouped into broader categories of research to provide a more generalized view for future research directions.

A chi-square test of homogeneity comparing respondents' primary occupation and years of active involvement in rice production with strategies implemented to control or mitigate herbicide-resistant weeds was performed using proc freq in SAS v9.4 (SAS Institute, Cary, NC 27513). Not all respondents provided an answer to every survey question. The total number of observations (n) are included for each survey question presented in the results and discussion sections.

RESULTS

Demographics

A total of 123 responses were received encompassing 34 out of 39 rice-producing counties, and accounting for 236,414 hectares out of the 583,152 harvested rice hectares (40.5%) in Arkansas for 2020 (Hardke, 2021) (**Table 1**). Of the 123 respondents, 55, 45, 19, and 4 respondents reported their primary occupation as farmer, consultant, industry representative, and "other", respectively (**Table 1**). Respondents that selected "other" each fell into more than one of the designated categories. Most survey participants (75%) had been actively involved in rice production for 11 years or more ($n = 122$) (data not shown). Fifty percent had been actively involved in rice production for 21 years or more. Only 5% of survey participants had been active in rice production for <6 years.

TABLE 1 | Occupation and rice hectares of respondents collected from a rice weed management survey conducted in 2020 in Arkansas, USA ($n = 123$).

	Primary occupation		Rice hectares	
Occupation	Frequency	Percent %	Hectares	Percent %
Farmer	55	45	32,563	14
Consultant	45	37	168,861	71
Industry rep	19	15	32,946	14
Other	4	3	2,044	1
			Total = 236,414	

Problematic Rice Weeds and Perceived Weed Research Needs

A total of 105 responses were returned for flooded rice and 92 responses were returned for furrow-irrigated rice regarding the most problematic weed species in the respective production systems. Results revealed that in flooded rice the most problematic weeds were ECG, followed by *Cyperus* spp., and *Oryza sativa* L., respectively, while in furrow-irrigated rice they were, in order of importance, ECG, *Amaranthus palmeri* S. Wats., and *Cyperus* spp. (**Figure 1**). ECG recorded the largest total number of points in flooded (292 of a possible 315) and furrow-irrigated rice (236 of a possible 276) indicating nearly every respondent considered ECG to be the #1 most problematic weed species in rice, regardless of growing environment. *Cyperus* spp. included *Cyperus iria* L., *Cyperus esculentus* L., *Cyperus difformis* L., *Cyperus flavicomus* Michx., and the generic term "sedges". *Oryza sativa* L., the third most problematic weed in flooded rice, was the sixth most problematic weed in furrow-irrigated rice. *Diplachne* spp. were perceived as the fourth most problematic weeds in flooded rice and fifth most problematic in furrow-irrigated rice. Other problematic weeds reported in flooded rice by respondents were *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster, *Aeschynomene virginica* (L.) B.S.P., *Amaranthus palmeri* S. Wats., *Sesbania herbacea* (P. Mill) McVaugh, and *Digitaria* spp. In furrow-irrigated rice, other reported weeds included *Digitaria* spp., *Sesbania herbacea* (P. Mill) McVaugh, *Sorghum halepense* (L.) Pers., *Eleusine indica* (L.) Gaertn., and *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster. Therefore, the top two problematic broadleaf weeds in flooded rice were *Amaranthus palmeri* S. Wats. and *Aeschynomene virginica* (L.) B.S.P., while the top two problematic broadleaf weeds in furrow-irrigated rice were *Amaranthus palmeri* S. Wats. and *Sesbania herbacea* (P. Mill) McVaugh.

Results from the question that asked respondents to provide two areas of weed management research that would benefit their operation's profitability and/or overall weed control are presented in **Figure 2**. Singular keywords or phrases detected most frequently in responses indicated research needs including "*Echinochloa-crus-galli*" and "MOA" (modes-of-action),

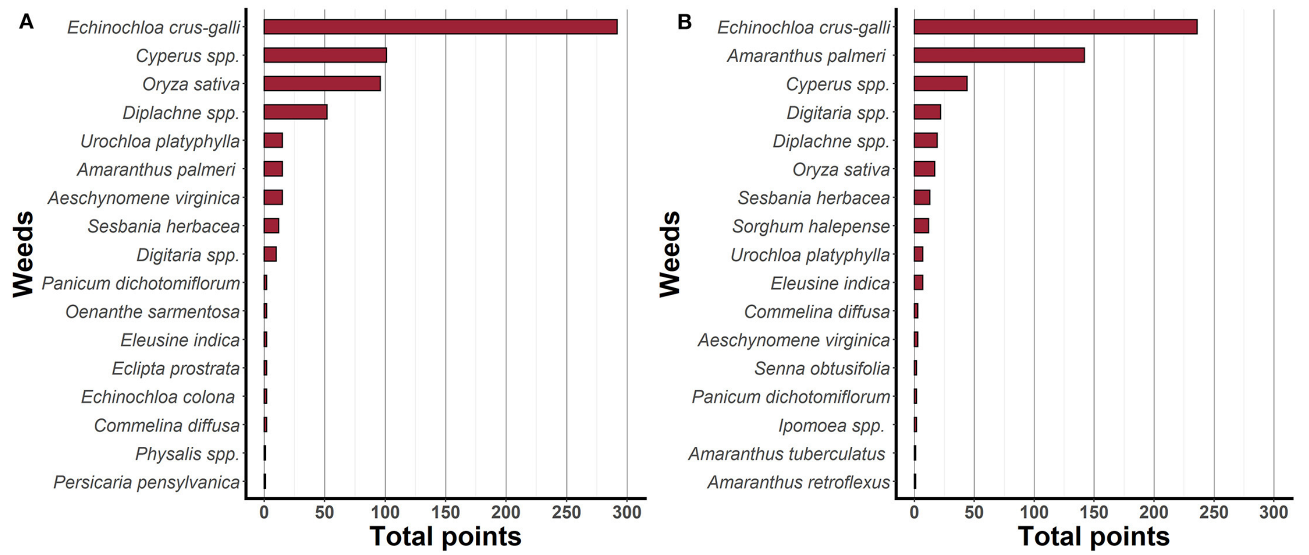

FIGURE 1 | Most problematic weed species reported in **(A)** paddy rice ($N = 105$) and **(B)** furrow-irrigated-rice ($N = 92$). Weeds listed as the #1, #2, and #3 most problematic were awarded 3, 2, and 1 points, respectively. Greater total points indicate the respective weed species was more consistently listed as a top problematic weed species in Arkansas rice hectares. **(A)** *Cyperus* spp. included: *Cyperus* spp. (56), *Cyperus iria* L. (38), *Cyperus esculentus* L. (3), *Cyperus flavicomus* Michx. (2), and *Cyperus difformis* L. (2). **(B)** *Cyperus* spp. included: *Cyperus* spp. (34), *Cyperus iria* L. (6), *Cyperus difformis* L. (3), and *Cyperus esculentus* L. (1).

followed by "residual", "resistance", "preemergence", and "grass" (**Figure 2A**). The most generalized common area of weed science research requested by survey respondents was "Control of *Echinochloa crus-galli*" (27 responses) (**Figure 2B**). "Preemergence or residual herbicide effectiveness" and "development of new modes of action or chemistry" each received 21 responses as an important area of research that would benefit rice production. "Herbicide resistance" (16 responses) was the only other reported research need by survey participants to receive a minimum of 10 responses [excluding the catch-all "other" category that included broad-spectrum topics such as biology, agronomy, identification, etc. (12 responses)].

Twelve current research or educational efforts were also rated by importance on a scale of 1 to 5, (where 1 = not important, 2 = slightly important, 3 = moderately important, 4 = very important, and 5 = extremely important). Respondents perceived development of new herbicide options as very important with the highest average ranking of 4.79 (**Table 2**). One important comment made by a survey participant was, "We need novel solutions to resistance issues. Nothing is working!" However, effective, non-chemical approaches to weed management were ranked as the least important current research or educational effort with an average ranking of 2.97 (slightly to moderately important).

Herbicide-Resistant Weeds

Ninety responses were returned regarding the rate of concern for herbicide-resistant weeds (data not shown). Seventy-eight percent of survey participants reported high concern with herbicide-resistant weeds while 21 and 1% of respondents reported moderate and slight concern, respectively. Among farmer respondents, 67% reported high concern with herbicide-resistant weeds while 86% of consultants, 83% of industry representatives, and 100% of other respondents reported high concern with herbicide-resistant weeds (data not shown).

Eighty-four percent of survey respondents also indicated they are managing herbicide-resistant weeds (excluding ECG) currently in their rice hectares (**Table 3**). When asked to provide the weeds (excluding ECG) and herbicides to which they were resistant, 39% of the respondents (44) reported *Cyperus iria* L. as resistant to acetolactate synthase (ALS)-inhibitors and synthetic auxin herbicides (**Table 4**). *Oryza sativa* L. received the second highest number of responses (19 responses, 17%) and was believed to be resistant to ALS-inhibiting herbicides. Third was *Diplachne* spp. (13%), thought to be resistant to acetyl-CoA carboxylase (ACCase)-inhibiting, Photosystem II (PSII)-inhibiting, and ALS-inhibiting herbicides. Fourth was *Amaranthus palmeri* S. Wats. (12%) believed to be resistant to synthetic auxins, PSII-inhibitors, protoporphyrinogen oxidase (PPO)-inhibitors, and 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS)-inhibitor.

Eighty-six responses were returned for the question, "Are you implementing any strategies to minimize the occurrence of new herbicide-resistant weeds or spread of resistance?" Thirteen percent of the total number of respondents were not implementing any strategy to minimize the occurrence of new herbicide-resistant weeds or spread of resistance (**Table 3**).

Seventy-two survey participants that indicated they suspected herbicide-resistant weeds in their rice fields responded to, "What strategies are you using to control herbicide-resistant weeds?" A chi-square test of homogeneity revealed that strategies implemented to control the herbicide-resistant weeds were not

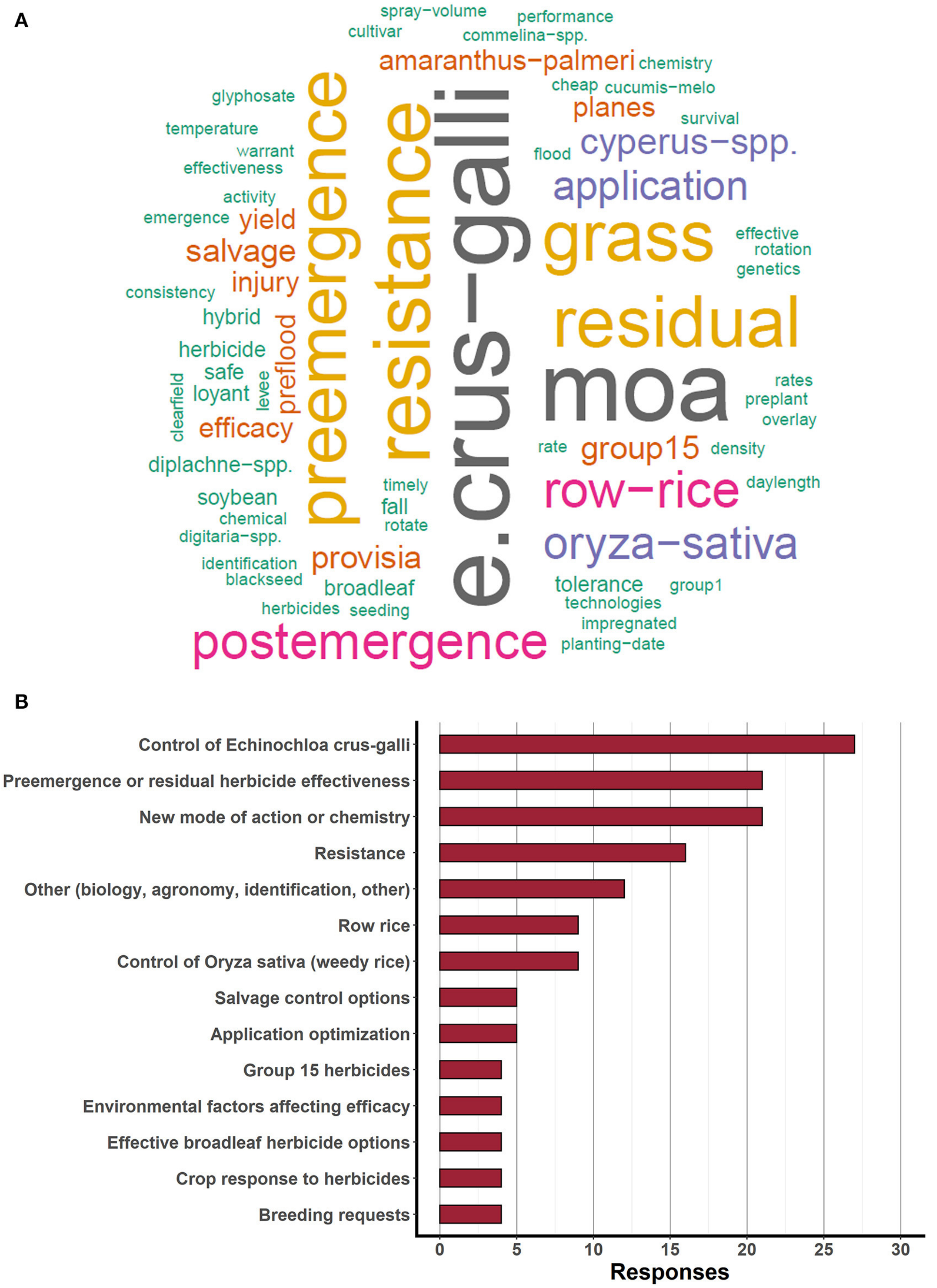

FIGURE 2 | Results for perceived areas of weed management research needs that would benefit rice producers' operation's profitability and/or overall weed control as reported by survey respondents. **(A)** WordCloud analysis of singular keywords or phrases generated from responses for rice weed management research needs. Words with a similar size and color received a similar number of responses. The larger the word, the more responses that keyword received [i.e., *Echinochloa-crus-galli* and MOA (mode-of-action) were the top two responses]. Some respondents provided more than one keyword resulting in a total number of observations greater than individual respondents (n = 124). **(B)** Groupings of perceived areas into broader categories of research to provide a more generalized view for future research directions (n = 76).

dependent on occupation type (chi-square = 2.9, P = 0.82) nor on number of years of involvement in rice production of survey participants (chi-square = 7.3, P = 0.69). Therefore, averaged across all respondents, the most commonly used method reported for managing herbicide-resistant weeds was crop rotation (85%, either alone or in conjunction with

TABLE 2 | Importance of current research or educational efforts as rated by survey respondents on a scale of 1–5, where 1 = not important, 2 = slightly important, 3 = moderately important, 4 = very important, and 5 = extremely important.

Research or educational effort	Mean ranking
Development of new herbicide options	4.79
Control strategies for herbicide-resistant weeds	4.46
Rice tolerance to new herbicides	4.27
Strategies to reduce the occurrence and spread of resistant weeds	4.20
Herbicide resistance screening program [ex. *Echinochloa crus-galli* (L.) P. Beauv., annual *Cyperus* spp.]	4.09
Impact of uncontrolled weeds on rice yields and overall economics	4.02
Expansion of weed control options in row rice	4.00
Performance of current herbicides	3.98
Economical weed control programs	3.93
Application optimization (nozzles, spray volume, adjuvants, etc.)	3.85
Impact of off-target herbicide movement and injury to rice	3.56
Effective, non-chemical approaches to weed management	2.97
	***n* = 91**

TABLE 3 | Respondents' suspicion of the existence of herbicide-resistant weeds [excluding *Echinochloa crus-galli* (L.) P. Beauv.] in the rice fields they farm or scout and whether they were implementing strategies to minimize the occurrence of herbicide resistance evolution or spread of resistance.

	Answer	Responses	Percent %
Suspect herbicide-resistant weeds [excluding *Echinochloa crus-galli* (L.) P. Beauv.]	Yes	76	84
	No	14	16
		***n* = 90**	
Employing strategies to minimize the occurrence of herbicide resistance evolution or spread of resistance	Yes	75	87
	No	11	13
		***n* = 86**	

other strategies) (**Table 5**). Eighty-one percent of respondents indicated the use of alternative herbicides either alone or in combination with other methods to manage herbicide-resistant weeds (**Table 5**). However, 5% of survey participants were using solely alternative herbicides to manage herbicide-resistant weeds (data not shown). Seed (trait) selection (38%), weed seedbank management (31%), and earlier rice planting (24%), were the next most commonly reported methods for managing herbicide-resistant weeds (**Table 5**).

Although crop rotation was listed as a primary method for managing herbicide-resistant weeds, 48% of respondents indicated 10% or more of their reported hectares were in continuous rice (3 consecutive years or more) (**Figure 3**). When weighted by number of hectares reported, 18% of the total hectares were designated as continuous rice (data not shown). Multiple reasons were provided by respondents as limitations for rice rotation to other crops (**Figure 4**). Twenty-nine percent of respondents indicated field/soil type was the main limitation for rice rotation to other crops, followed by zero-grade fields (28%) and commodity prices/profitability (23%), respectively.

In addition to strategies utilized for managing already established herbicide-resistant weeds, survey participants were asked what strategies, if any, were being implemented to mitigate the evolution of new herbicide-resistant weeds and the spread of current herbicide resistance. Similar to management strategies for current herbicide-resistant weeds, the most commonly implemented mitigation strategy was crop rotation (54%) followed by the use of multiple mode-of-action mixtures and overlapping residuals, each with 25% of respondents indicating use (**Table 5**). One interesting note, of the 16 strategies that were reported to mitigate herbicide resistance, half involved the use of or improvement of chemical control strategies (**Table 5**).

Echinochloa crus-galli

Respondents ($n = 85$) reported that 92% of their rice hectares were infested with ECG equating to 174,323 of a possible 189,522 reported hectares (data not shown). Additionally, 72 survey respondents indicated they believed they had herbicide-resistant ECG on their farm ($n = 84$, 86%) (**Table 6**).

Respondents listed nine different herbicide sites-of-action in which they believed ECG to be resistant to in their rice hectares (**Table 6**). Most respondents indicated they believed their ECG to be resistant to PSII-inhibitors (WSSA Group 5) (80%), quinclorac synthetic auxin (WSSA Group 4) (80%) and ALS-inhibitors (WSSA Group 2) (79%) (**Table 6**). Furthermore, 87% of respondents perceived ECG to be multiple-resistant to three sites-of-action or more (**Table 6**).

Survey participants reported that their first postemergence herbicide application for ECG control often failed. Fifty-two percent of respondents indicated that the first postemergence application failed > 40% of the time with an overall average of 44% of the time (**Figure 5**). Therefore, almost half of the first postemergence herbicide applications fail to successfully control ECG. After this initial failure from the first postemergence herbicide application, most respondents (53%) believed that two additional postemergence applications were required to effectively control the ECG escapes (**Figure 5**). Even more concerning, 17 respondents (21%) replied "I never control it" after the initial herbicide failure. When asked to rank the importance of the factors in causing failure of herbicides to control ECG on their farm or scouted hectares on a 1–5 scale (where 1 = not important, 2 = slightly important, 3 = moderately important, 4 = very important, and 5 = extremely important), survey participants perceived herbicide resistance, herbicide selection and weed size at application to be very important (with ranks of 4.28, 4.22, and 4.06, respectively) (**Table 7**). They also perceived lack of adequate coverage and environmental conditions as moderately to very important with ranks of 3.80 and 3.72, respectively.

ECG densities in the absence of herbicide use (germination potential within a given year based on the soil seedbank) were described to be between 11 and 107 plants m^{-2} on average by more than half of the respondents (51%) (**Table 8**). Although the seedbank is plentiful and germination potential is high, 44% of survey respondents thought ECG densities were from 0 to 1

TABLE 4 | Weed species [excluding *Echinochloa crus-galli* (L.) P. Beauv.] suspected of herbicide resistance as reported by survey respondents and the herbicide site-of-action and WSSA Group # to which they are suspected resistant to.

Weeds	Responses	Site-of-action	WSSA Group #
Cyperus iria L.	44	ALS-inhibitors, Synthetic auxins	2, 4
Oryza sativa L.	19	ALS-inhibitors	2
Diplachne spp.	15	ACCase-inhibitors, ALS-inhibitors, PSII-inhibitors	1, 2, 5
Amaranthus palmeri S. Wats.	13	ALS-inhibitors, Synthetic auxins, PPO-inhibitors, PSII-inhibitors, EPSPS-inhibitor	2, 4, 5, 9, 14
Cyperus esculentus L.	6	ALS-inhibitors	2
Persicaria pensylvanica (L.) M. Gomez	4	ALS-inhibitors, PPO-inhibitors	2, 14
Digitaria spp.	4	ACCase-inhibitors, ALS-inhibitors	1, 2
Cyperus difformis L.	3	ALS-inhibitors	2
Sesbania herbacea (P. Mill) McVaugh	2	PPO-inhibitors	14
Urochloa platyphylla (Munro ex C. Wright) R.D. Webster	1	ACCase-inhibitors	1
Eclipta prostrata (L.) L.	1	ALS-inhibitors	2
Cyperus flavicomus Michx.	1	Synthetic auxins	4
	***n* = 64**[a]		

[a] *The number of individual respondents was 64; however, respondents were permitted to provide more than one answer resulting in a total number of weed species responses greater than the number of individual respondents. #, number.*

plants m^{-2} at rice harvest in 2020, while 41% believed they were from 2 to 10 plants m^{-2} (**Table 8**).

Survey respondents indicated very similar strategies were employed for ECG control as the aforementioned herbicide-resistant weeds control (**Table 5**). The chi-square test of homogeneity revealed that strategies implemented to manage ECG were not dependent on occupation type of survey participants (chi-Square = 13.1, $P = 0.16$) nor on number of years of involvement in rice production (chi-Square = 12.6, $P = 0.81$). Most survey participants (81%) were using crop rotation alone or in combination with other strategies to manage ECG and alternative herbicides (69%) was the second most commonly used tactic alone or in combination with other strategies to manage ECG (**Table 5**). Other non-chemical ECG control strategies including seedbank management (24%) and earlier planting dates (30%) were only moderately used.

Cost of Rice Weed Control

The average cost of chemical weed control for reported rice hectares was evaluated during the survey. The perceived average cost of chemical control in rice weighted by hectares reported per respondent was \$266.20 ha^{-1} ($n = 113$) (**Figure 6**). When asked, "What percent of your overall herbicide expense this year was for ECG control?", survey participants estimated ∼81% of the total herbicide cost was attributed to ECG which equated to an average cost of \$215.90 ha^{-1} (data not shown).

Survey participants were also asked to evaluate the average yield loss on their farms attributed to ECG. Most participants estimated rice yield loss attributed to ECG of 455–959 kg ha^{-1} (29%) and 203–454 kg ha^{-1} (29%) (**Table 9**). Using the average price of \$264.50 per metric ton of rough rice in 2020 (USDA-NASS, 2022), the corresponding economic loss would be \$121–254 ha^{-1} and \$54–120 ha^{-1} for 455–959 kg ha^{-1} and 203–454 kg ha^{-1}, respectively (**Table 9**). Survey participants were also asked to evaluate the yield loss in their most heavily infested rice field. Most participants (29%) estimated yield loss of 708–1,464 kg ha^{-1} and 22% of respondents perceived the estimated yield loss to be 1,465–2,221 kg ha^{-1}. The corresponding economic loss would be \$188–387 ha^{-1} and \$388–588 ha^{-1} for 708–1,464 kg ha^{-1} and 1,465–2,221 kg ha^{-1}, respectively.

DISCUSSION

Problematic Rice Weeds and Perceived Weed Research Needs

The prevalence of ECG as the most detrimental weed in Arkansas rice is consistent with previous survey data that reported it as the most problematic weed in rice production systems (Norsworthy et al., 2007, 2013). ECG was detected in the seedbank of most major cropping systems of Arkansas, and it has a prolonged emergence period from mid-April to late September that contributes to the weeds' success (Bagavathiannan et al., 2011). *Cyperus* spp. have drastically risen on the Arkansas rice problematic weeds list since the previous survey was conducted in 2011 (Norsworthy et al., 2013). In the previous survey, *Cyperus esculentus* L. was reported as the 8th most problematic weed, and *Cyperus iria* L. was not ranked in the top 20; data from the current survey conducted nearly a decade later resulted in the combination of *Cyperus* spp. being the 2nd most problematic weed species to combat in rice hectares. The presence and spread of ALS-inhibitor-resistant *Cyperus esculentus* L. and *Cyperus iria* L. (Norsworthy et al., 2007) might be a major reason why *Cyperus* spp. are considered so problematic in Arkansas rice.

Oryza sativa L. has held constant as a top four problematic weed species in Arkansas rice as it was previously ranked third in importance and the fourth problematic weed in 2011 (Norsworthy et al., 2013), and more recently, Burgos et al. (2021) also reported it as the third most problematic weed. With infestation levels up to 1,076 plants m^{-2} (Burgos et al.,

TABLE 5 | Strategies reported from respondents being used to control herbicide-resistant weeds and *Echinochloa crus-galli* (L.) P. Beauv. and to mitigate the evolution of herbicide-resistant weeds[a].

		Other herbicide-resistant weeds	*Echinochloa crus-galli* (L.) P. Beauv.
		Responses	Responses
Strategies used to control herbicide-resistant weeds	Crop rotation	61	68
	Alternative herbicides	58	58
	Seed (trait) selection	27	35
	Seedbank management	22	20
	Earlier planting dates	17	25
	Cover crops	3	2
	Fall deep tillage	3	1
	Other[b]	2	3
	None	1	3
	Pinpoint flood	0	1
		***n* = 72**	***n* = 84**
Strategies used to mitigate the evolution of herbicide-resistant weeds	Crop rotation	35	
	Multiple modes-of-action mixtures	16	
	Overlapping residuals	16	
	Rotating chemistries	11	
	Technology/trait rotation	9	
	Start with preemergence herbicide	7	
	Start clean	6	
	Weed seed prevention	6	
	Full use rate	5	
	Application emphasis	4	
	Early flooding	3	
	Fallow rotation	3	
	Sanitation	2	
	Tillage reduction or elimination	2	
	Early planting	1	
	Flushing to activate herbicides	1	
		***n* = 65**	

[a]*The number of individual respondents for controlling herbicide-resistant weeds and Echinochloa crus-galli (L.) P. Beauv. was 72 and 84, respectively; for mitigating the evolution of herbicide-resistant weeds the number of individual respondents was 65; however, respondents were permitted to provide more than one answer resulting in a total number of responses greater than the number of individual respondents.*
[b]*Other responses included: Overlapping residuals, preventing emergence, and spraying Echinochloa crus-galli (L.) P. Beauv. when small.*

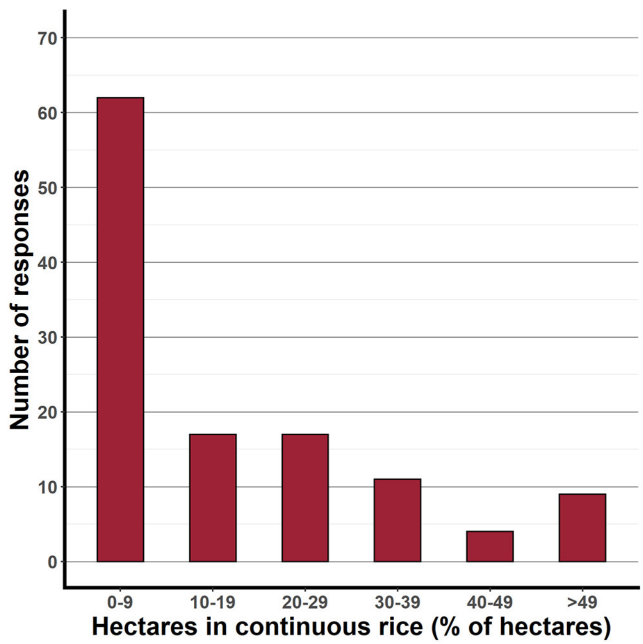

FIGURE 3 | Percentage of continuous rice hectares for 3 consecutive years or more (*n* = 120).

2021), multiple reasons might explain its prevalence including resistance to ALS-inhibiting herbicides and the morphological similarity to the rice crop. The prevalence of *Amaranthus palmeri* S. Wats. in furrow-irrigated rice as the second most troublesome weed is not surprising as it is one of the two most troublesome weeds in Arkansas soybean [*Glycine max* (L.) Merr.] (Riar et al., 2013b) and furrow-irrigated production removes the cultural practice of flooding as a management tactic. Also, *Amaranthus palmeri* S. Wats. has evolved resistance to eight different sites-of-action in Arkansas (Barber et al., 2022; Heap, 2022), making it persistent and difficult-to-control across cropping systems. Soybean is the most common rotational crop with rice (Burgos et al., 2021); therefore, the rise of occurrence and herbicide resistance in soybean cropping systems is likely to promote the increase of *Amaranthus palmeri* S. Wats. infestations in rice fields (Norsworthy et al., 2013).

Although *Diplachne* spp. dropped from the second most problematic weed species in Arkansas rice in 2011 (Norsworthy et al., 2013) to the fourth and fifth most problematic species in flooded and furrow-irrigated rice, respectively, in the present survey, their occurrence of remaining in the top five most problematic weeds indicates persistence and difficult-to-manage nature. In 2006, *Aeschynomene virginica* (L.) B.S.P. and *Persicaria* spp. were the two most problematic broadleaf weeds (Norsworthy et al., 2007), while *Aeschynomene virginica* (L.) B.S.P. and *Amaranthus palmeri* S. Wats. were the two most problematic broadleaf weeds in 2011 (Norsworthy et al., 2013). Excluding *Amaranthus palmeri* S. Wats. in furrow-irrigated rice production, minimal broadleaves were reported in the present survey as truly problematic likely due to the morphological difference from rice and the presence of multiple effective herbicide options (Barber et al., 2022).

The most common area of weed management research reported to benefit the respondent's operation profitability and/or overall weed control was "Control of *Echinochloa crus-galli*" which was similar to the 2011 survey where ECG control was the most common weed research area recommended by respondents

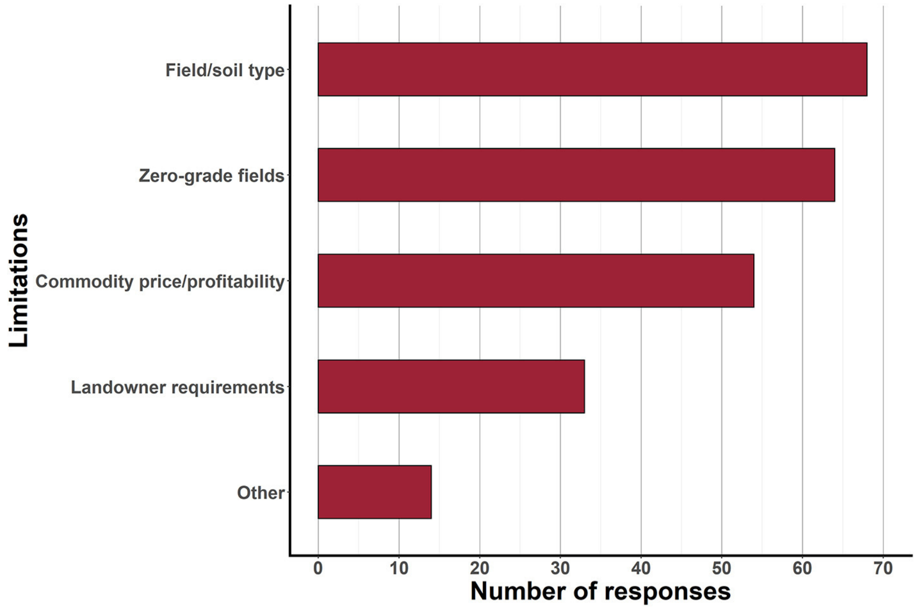

FIGURE 4 | Reported limitations for crop rotation from rice to other cropping systems (n = 118, 233 total responses).

(Norsworthy et al., 2013). Major reasons for this request might include the high infestation levels of ECG when left uncontrolled, reduced commodity price when rice seeds are contaminated with ECG seeds, and the presence of ECG seedbank in most Arkansas cropping systems (cotton, soybean, rice). The request of "pre-emergence herbicides" as a major area of research might be due to failure of postemergence control of weeds in the previous growing seasons, the slower evolution of resistance to some soil applied herbicides, and better understanding the probability for rice injury, causes, and yield loss potential.

The request for research of new modes-of-action or chemistry is likely due to the escalation of herbicide resistance to the existing modes-of-action, the lack of introduction of new herbicides, continued failed attempts at successful weed control, and the continued search for an easy method of weed control. Even though discovery of herbicides with new mechanisms-of-action may help to manage herbicide-resistant weeds, changes in the patterns of herbicide use are required to reduce herbicide resistance evolution (Gaines et al., 2021). Ranking effective, non-chemical approaches to weed management as the least important current research or educational effort, is an indication that a paradigm shift in rice producers' weed control line of thought is needed with dwindling herbicide options due to herbicide resistance.

Herbicide-Resistant Weeds

High herbicide resistance concerns reported in the present research are similar to survey results from nearly a decade ago. Norsworthy et al. (2013) also reported moderate or high concern regarding herbicide resistance from 98% of participants, with resistant weeds suspected in rice fields scouted by 88% of consultants. In Arkansas, resistance has been documented in several major weeds that respondents reported including *Oryza sativa* L. (ALS-inhibitors), *Cyperus iria* L. (ALS-inhibitors), *Cyperus difformis* L. (ALS-inhibitors), *Echinochloa colona* (L.) Link (ALS-inhibitors, PSII-inhibitors, and synthetic auxins), *Cyperus esculentus* L. (ALS-inhibitors), and *Persicaria pensylvanica* (L.) M. Gomez (ALS-inhibitors) (Heap, 2022). However, there have been no confirmed cases of resistance for many of the other herbicides and weeds listed by survey participants which implies that control failure in these cases might be due to factor(s) other than resistance (Norsworthy et al., 2012).

Although respondents provided some alternative weed management strategies to chemical control methods, more efforts (research, educational, and on-farm implementation) are needed to diversify strategies. Breeding of more competitive cultivars, robotic systems for weed control, and use of RNA to silence key weed genes through the process of RNA interference (RNAi) are all potential future options to enhance rice weed management efforts (Westwood et al., 2018). "Breeding efforts" were minimally requested by survey participants as important future weed management research needs (**Figure 2**). However, breeding new rice cultivars with a competitive advantage over weeds (Shrestha et al., 2020) might help to reduce selection pressure. Additional cultural methods pertaining to breeding or cultivar selection include selection of hybrid rice lines with greater tillering and taller growth characteristics (Shivrain et al., 2009), selection of more competitive rice cultivars and optimizing agronomic conditions (Gealy and Duke, 2017), and full-season cultivars that maximize the period with crop cover (Reddy and Norsworthy, 2010).

Earlier planting dates have been implemented as a strategy to combat herbicide-resistant weeds (**Table 5**), but could be

TABLE 6 | Herbicide resistance in *Echinochloa crus-galli* (L.) P. Beauv. across Arkansas rice hectares as reported by survey respondents[a].

		Answer	Responses
Do you suspect herbicide-resistant *Echinochloa crus-galli* (L.) P. Beauv.?		Yes	72
		No	12
			***n* = 84**
	Herbicide	**WSSA Group #**	**Responses**
What herbicides do you suspect resistance to?	Photosystem II inhibitor	5	57
	Synthetic auxin (quinclorac)	4	57
	ALS-inhibitor	2	56
	ACCase-inhibitor	1	33
	EPSPS-inhibitor	9	29
	DOXP synthase inhibitor	13	21
	Synthetic auxin (florpyrauxifen-benzyl)	4	19
	Microtubule inhibitor	3	14
	Lipid synthesis inhibitor	8	11
			***n* = 71**[b]
		# of sites-of-action	**Responses**
Reported multiple resistance in *Echinochloa crus-galli* (L.) P. Beauv.		One	1
		Two	8
		Three	24
		Four	14
		Five	10
		Six	7
		Seven	1
		Eight	2
		Nine	4
			***n* = 71**

[a] *Florpyrauxifen-benzyl and quinclorac were treated as different sites-of-action.*
[b] *The number of individual respondents was 71; however, respondents were permitted to provide more than one answer regarding herbicides that they suspected resistance to resulting in a total number of responses greater than the number of individual respondents. #, number.*

adopted to a wider extent, especially as a strategy to mitigate the evolution of herbicide resistance development. By planting rice earlier, it provides the crop a competitive advantage by emerging and growing prior to the optimum emergence window for some of our most problematic rice weed species like ECG, *Panicum dichotomiflorum* Michx., and *Amaranthus* spp. (Werle et al., 2014). Additionally, winter flooding, seed burial depth, and the stale seedbed technique can help to reduce the size of soil seedbank and weed infestation (Franca et al., 2020). Preventive measures such as weed-free certified seeds and equipment sanitation are also essential (Norsworthy et al., 2012; Riar et al., 2013a). Crop rotation is crucial and has been previously recommended as a key strategy for controlling herbicide-resistant ECG (Norsworthy et al., 2007) and *Oryza sativa* L. (Norsworthy et al., 2007; Burgos et al., 2021). The most common rotations in Arkansas are rice–soybean, rice–soybean–corn (*Zea mays* L.), and rice–fallow–soybean (Burgos et al., 2021) with soybean being the most compatible rotational crop with rice because it allows for alternative herbicide programs to be utilized and increases ease of controlling grass species in a broadleaf crop (Burgos et al., 2008).

Although crop rotation has great benefits for weed management and many survey respondents indicated they used this strategy for the management of herbicide-resistant weeds (**Table 5**), nearly 1/5th of reported rice hectares were under continuous rice production (≥3 years) which is a concerning practice affecting successful long-term weed management. Proportions of different rice varieties grown were not assessed in the present survey, but a previous survey reported imidazolinone-resistant rice was planted on 64% of the planted rice hectares, 42% of which was treated exclusively with an ALS-inhibiting herbicide for grass control (Norsworthy et al., 2013). Therefore, the probability of continuous rice hectares receiving repetitive herbicide treatments annually is high, resulting in the continued selection for herbicide-resistant weeds. Continued education efforts must be implemented to warn against the overuse of specific herbicide technologies and demonstrate the importance of integrated weed management strategies for long-term weed management success.

In Arkansas, several factors such as decreased labor, ease of management, and potentially fewer input costs increased the interest in precision-leveling fields to zero grade (Hardke, 2021). Unfortunately, zero-grading land constrains growers to a continuous rice production system due to limited water movement inhibiting other non-flooded crop production (Hardke, 2018). Although this practice provides some benefits to Arkansas growers, the crop rotation limitation and resulting monoculture agricultural system establishes a weed spectrum that thrives in that specific environment and quickly adapts to the repeated similar management strategies.

Echinochloa crus-galli

ECG was reported as the most problematic weed species in both flooded and furrow-irrigated rice hectares (**Figure 1**), with 92% of respondents indicating the presence of ECG in their rice fields. With the occurrence of ECG populations with multiple resistance in the midsouthern U.S. (Barber et al., 2022; Heap, 2022), it is logical that a large proportion of the rice weed control budget would be directed toward ECG control. This may also partially explain the high proportion of reported postemergence herbicide failures, in addition to the inconsistency in control observed from herbicides selectively targeting ECG, a very morphologically similar weed species to rice.

In Arkansas, research has documented ECG resistance to six sites-of-action (when considering quinclorac and florpyrauxifen-benzyl as two separate sites-of-action within synthetic auxins): ACCase-inhibitors (WSSA Group 1), ALS-inhibitors (WSSA

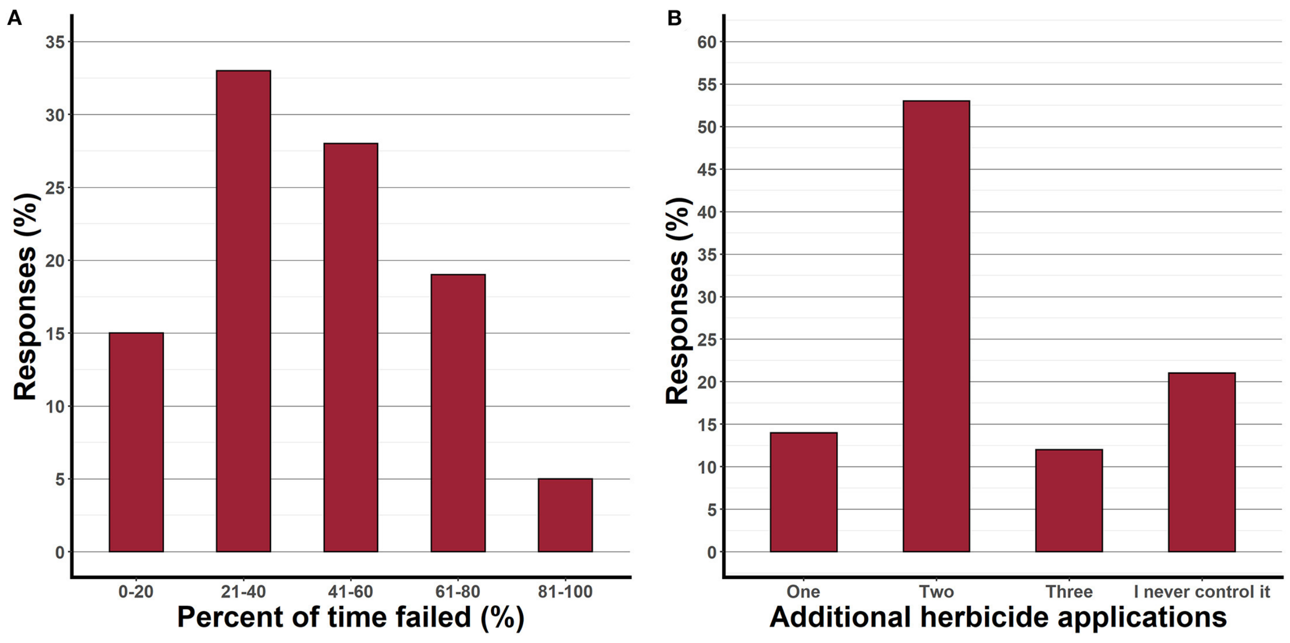

FIGURE 5 | Responses for **(A)** percent of the time that respondents failed to effectively control *Echinochloa crus-galli* (L.) P. Beauv. with the first postemergence herbicide application ($n = 100$) and **(B)** the average number of additional applications required for *Echinochloa crus-galli* (L.) P. Beauv. control if the initial application fails ($n = 81$).

TABLE 7 | Importance of factors causing herbicide failure on *Echinochloa crus-galli* (L.) P. Beauv. control as reported by survey respondents[a].

		Mean response
Importance of factors causing herbicide failure	Resistance	4.28
	Herbicide selection	4.22
	Weed size at application	4.06
	Lack of adequate coverage	3.80
	Environmental conditions	3.72
		***n* = 81**

[a]*Importance was ranked by respondents on a 1–5 scale, where 1 = not important, 2 = slightly important, 3 = moderately important, 4 = very important, and 5 = extremely important.*

TABLE 8 | Reported *Echinochloa crus-galli* (L.) P. Beauv. densities if herbicides were to not be applied (germination potential within a given year based on the soil seedbank) and the actual *Echinochloa crus-galli* (L.) P. Beauv. density present in respondents' 2020 rice crop at harvest.

	Density Plants m^{-2}	Responses #	Percent %
Which of the following densities best describes the *Echinochloa crus-galli* (L.) P. Beauv. population on your farm if herbicides were to not be applied?	0–1	2	2.5
	2–10	13	16.0
	11–107	41	50.6
	108–1,075	19	23.5
	>1,075	6	7.4
		***n* = 81**	
Which of the following densities best describe the *Echinochloa crus-galli* (L.) P. Beauv. population in your 2020 rice crop at harvest?	No ECG present	3	3.7
	0–1	36	44.4
	2–10	33	40.7
	11–107	8	9.9
	108–1,075	1	1.2
	>1,075	0	0.0
		***n* = 81**	

#, number.

Group 2), synthetic auxin (quinclorac, WSSA Group 4), synthetic auxin (florpyrauxifen-benzyl, WSSA Group 4), PSII-inhibitor (WSSA Group 5), and DOXP-inhibitor (WSSA Group 13) (Barber et al., 2022; Heap, 2022). Present survey results indicated respondents believed ECG was resistant to a total of nine different sites-of-action (**Table 6**). Therefore, either there are undocumented instances of herbicide resistance to additional sites-of-action within the state of Arkansas, or these herbicide failures are the result of other factors such as suboptimal environmental conditions, application errors, weed size, or herbicide selection (**Table 7**). The lack in implementation of alternative, diverse weed management strategies (**Table 5**) compromise the sustainability of current weed management options.

Postemergence herbicide failures on ECG were common as reported by survey respondents, and twenty-one percent of survey participants said "I never control ECG" following failure of the first postemergence application (**Figure 5**). In addition

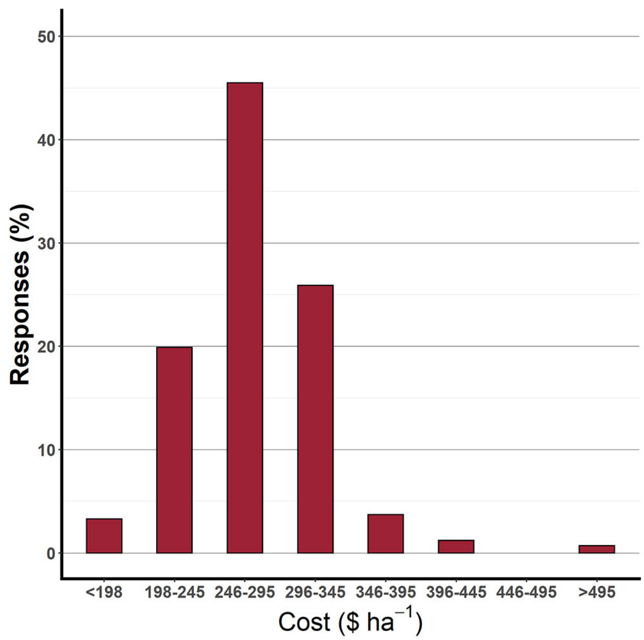

FIGURE 6 | Estimated rice weed control cost ha^{-1} weighted by hectare reported per respondent (n = 113).

TABLE 9 | Estimated average rice yield loss attributed to *Echinochloa crus-galli* (L.) P. Beauv. in Arkansas rice fields and estimated yield loss in most heavily infested fields (maximum potential loss) as reported by survey respondents.

	Estimated yield loss kg ha^{-1}	Value of yield loss[a] US $ ha^{-1}	Responses	Percent %
Average	0–202	0–53	22	26.8
	203–454	54–120	24	29.3
	455–959	121–254	24	29.3
	960–1,464	255–387	9	11.0
	1,465–1,969	388–521	2	2.4
	≥1,970	≥522	1	1.2
			***n* = 82**	
Heavily-infested fields	0–707	0–187	17	20.7
	708–1,464	188–387	24	29.3
	1,465–2,221	388–588	18	22.0
	2,222–2,979	589–788	13	15.9
	2,980–3,736	789–988	4	4.9
	3,737–4,493	989–1,189	3	3.7
	≥4,494	≥1,190	3	3.7
			***n* = 82**	

[a] *The value of yield loss in dollars was calculated using an average price of rough rice = $264.5 per metric ton (USDA-NASS, 2022).*

to inducing unacceptable yield loss for the simultaneous rice crop, ECG escapes can produce up to 39,000 seeds plant^{-1} (Bagavathiannan et al., 2012) that will increase the soil seedbank and compromise subsequent growing seasons. In Arkansas rice fields, the ECG seedbank was previously predicted to contain an average of 6,000 seeds m^{-2} with up to 215,000 seeds m^{-2} (Bagavathiannan et al., 2011). With 41% of respondents estimating 2–10 ECG plants m^{-2} at the 2020 harvest, this has the potential to increase the soil seedbank by 78,000–390,000 seeds m^{-2}. A primary recommendation for reducing the risks of herbicide resistance is the use of a diversified approaches to weed management that target the reduction of seed production and the number of weed seeds in the soil seedbank (Norsworthy et al., 2012).

Cost of Rice Weed Control

The high concern for herbicide-resistant weeds reported by respondents in their Arkansas rice hectares is alarming from multiple standpoints. However, one often overlooked facet of herbicide resistance is the significant increase in weed control costs as additional reactive management strategies are required to be implemented (Llewellyn et al., 2002) resulting in an average additional cost of $65.60 ha^{-1} that can reach up to $98 ha^{-1} (Norsworthy et al., 2013). Other additional estimated costs associated with herbicide-resistant weeds are crop yield loss, decreased commodity prices due to weed-seed contamination, and reduced land values (Norsworthy et al., 2012).

Season-long interference of ECG with densities between 1 and 20 plants m^{-2} reduced rice grain yield up to 301 kg ha^{-1} per ECG plant (Stauber et al., 1991) equating to approximately a $79 ha^{-1} loss for each additional ECG plant present with 2020 rough rice prices (USDA-NASS, 2022). This ECG density range was reported by >41% of respondents at 2020 Arkansas rice harvest (**Table 8**). Additionally, heavy infestations of ECG are known to reduce land value by removing 60–80% of nitrogen from the soil (Ottis and Talbert, 2007). In addition to ECG impacts on yield, land value, and the soil seedbank, this weed species is likely to contaminate rice seed at harvest leading to price dockages for the producer.

Although chemical weed control options tend to be simpler and offer increased short-term economic returns, the prevalence of postemergence herbicide failures reported by respondents (**Figure 5**) would significantly increase this cost. Furthermore, after an initial failure from the first postemergence herbicide application, most respondents (53%) believed that two additional postemergence applications were required to effectively control ECG escapes (**Figure 5**), resulting in an added expense of ~$150 ha^{-1} (Barber, personal communication).

Alternative integrated weed management practices are often more laborious to enact and may increase the immediate weed management expense. However, when shifting focus from short-term to long-term economics, and the potential for widespread, multiple site-of-action resistance rendering herbicides non-viable, chemical costs of weed control will drastically increase (Davis and Frisvold, 2017). The implementation of integrated weed management strategies for both the management of current herbicide-resistant weeds and the mitigation of future evolution of herbicide resistance is one of the most effective and economical long-term strategies we currently have today.

Respondents in the present survey indicated non-chemical weed management practices as the least important current research effort (**Table 2**); therefore, educational campaigns to enhance adoption are required with an emphasis placed on illustrating the economic benefits of integrated weed management strategies (Llewellyn et al., 2004).

CONCLUSIONS

ECG is the most problematic weed in Arkansas rice. Other major weeds such as *Cyperus* spp., *Oryza sativa* L., *Diplachne* spp., and *Amaranthus palmeri* S. Wats. are also problematic. Overreliance on chemical weed control cannot provide sustainable control of these weeds as herbicide resistance has been widely documented and is of high concern as indicated by survey respondents. Integrated weed management strategies are required to reduce selection pressure and improve long-term weed management success. However, effective, non-chemical approaches to weed management were ranked as the least important current research or educational effort, indicating a paradigm shift in rice producers' weed control line of thought is needed with dwindling herbicide options due to herbicide resistance. Educational efforts must be established highlighting the long-term weed management and potential economic return benefits by being proactive to implement diversified strategies rather than reactive. Information gathered from the survey provided direct insights into current rice weed management practices and a better understanding of current concerns with making accurate and efficient weed management decisions. Additionally, the information provided will be used to prioritize research and Extension outreach efforts moving forward to address stakeholder needs more effectively.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Arkansas Institutional Review Board (IRB). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

TB contributed to survey development, survey conduction and management, analysis, and writing of manuscript. KK contributed to analysis and writing of manuscript. JN contributed to survey development, analysis, and editing of manuscript. LB contributed to survey development and editing of manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2022.881667/full#supplementary-material

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